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<p>(54) Title: WAVEFORM BLENDING TECHNIQUE FOR TEXT-TO-SPEECH SYSTEM</p> <p>(57) Abstract</p> <p>A concatenator for a first digital frame with a second digital frame, such as the ending and beginning of adjacent diphone strings being concatenated to form speech is based on determining an optimum blend point for the first and second digital frames in response to the magnitudes of samples in the first and second digital frames. The frames are then blended to generate a digital sequence representing a concatenation of the first and second frames with reference to the optimum blend point. The system operates by first computing an extended frame in response to the first digital frame, and then finding a subset of the extended frame with matches the second digital frame using a minimum average magnitude difference function over the samples in the subset. The blend point is the first sample of the matching subset. To generate the concatenated waveform, the subset of the extended frame is combined with the second digital frame and concatenated with the beginning segments of the extended frame to produce the concatenated waveform.</p>			

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- 1 -

WAVEFORM BLENDING TECHNIQUE FOR TEXT-TO-SPEECH SYSTEM

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BACKGROUND OF THE INVENTION

Field of the Invention

15

The present invention relates to systems for smoothly concatenating quasi-periodic waveforms, such as encoded diphone records used in translating text in a computer system to synthesized speech.

20

Description of the Related Art

In text-to-speech systems, stored text in a computer is translated to synthesized speech. As can be appreciated, this kind of system would have wide spread application if it were of reasonable cost. For instance, a text-to-speech system could be used for reviewing electronic mail remotely across a telephone line, by causing the computer storing the electronic mail to synthesize speech representing the electronic mail. Also, such systems could be used for reading to people who are visually impaired. In the word processing context, text-to-speech systems might be used to assist in proofreading a large document.

25

However in prior art systems which have reasonable cost, the quality of the speech has been relatively poor making it uncomfortable to use or difficult to understand. In order to achieve good quality

- 2 -

speech, prior art speech synthesis systems need specialized hardware which is very expensive, and/or a large amount of memory space in the computer system generating the sound.

5 In text-to-speech systems, an algorithm reviews an input text string, and translates the words in the text string into a sequence of diphones which must be translated into synthesized speech. Also, text-to-speech systems analyze the text based on word type and context to generate intonation control used for adjusting the duration of the sounds and the pitch of the sounds involved in the speech.

10 Diphones consist of a unit of speech composed of the transition between one sound, or phoneme, and an adjacent sound, or phoneme. Diphones typically start at the center of one phoneme and end at the center of a neighboring phoneme. This preserves the transition between the sounds relatively well.

15 American English based text-to-speech systems, depending on the particular implementation, use about fifty different sounds referred to as phones. Of these fifty different sounds, the standard language uses about 1800 diphones out of possible 2500 phone pairs. Thus, a text-to-speech system must be capable of reproducing 1800 diphones. To 20 store the speech data directly for each diphone would involve a huge amount of memory. Thus, compression techniques have evolved to limit the amount of memory required for storing the diphones.

25 Prior art text-to-speech systems are described in part in United States Patent No. 8,452,168, entitled COMPRESSION OF STORED WAVE FORMS FOR ARTIFICIAL SPEECH, invented by Sprague; and United States Patent No. 4,692,941, entitled REAL-TIME TEXT-TO-SPEECH CONVERSION SYSTEM, invented by Jacks, et al. Further background concerning speech synthesis may be found in United States Patent No. 4,384,169, entitled METHOD AND APPARATUS FOR 30 SPEECH SYNTHESIZING, invented by Mozer, et al.

- 3 -

Two concatenated diphones will have an ending frame and a beginning frame. The ending frame of the left diphone must be blended with the beginning frame of the right diphone without audible discontinuities or clicks being generated. Since the right boundary of 5 the first diphone and the left boundary of the second diphone correspond to the same phoneme in most situations, they are expected to be similar looking at the point of concatenation. However, because the two diphone codings are extracted from different contexts, they will not look identical. Thus, blending techniques of the prior art have 10 attempted to blend concatenated waveforms at the end and beginning of left and right frames, respectively. Because the end and beginning of frames may not match well, blending noise results. Continuity of sound between adjacent diphones is thus distorted.

Notwithstanding the prior work in this area, the use of text-to- 15 speech systems has not gained widespread acceptance. It is desirable therefore to provide a software only text-to-speech system which is portable to a wide variety of microcomputer platforms, produces high quality speech and operates in real time on such platforms.

SUMMARY OF THE INVENTION

20 The present invention provides an apparatus for concatenating a first digital frame with a second digital frame of quasi-periodic waveforms, such as the ending and beginning of adjacent diphone strings being concatenated to form speech. The system is based on determining an optimum blend point for the first and second digital frames in response to the magnitudes of samples in the first and second 25 digital frames. The frames are then blended to generate a digital sequence representing a concatenation of the first and second frames, with reference to the optimum blend point. This has the effect of providing much better continuity in the blending or concatenation of

- 4 -

diphones in text-to-speech systems than has been available in the prior art.

5 Further, the technique is applicable to concatenating any two quasi-periodic waveforms, commonly encountered in sound synthesis or speech, music, sound effects, or the like.

10 According to one aspect of the present invention, the system operates by first computing an extended frame in response to the first digital frame, and then finding a subset of the extended frame which matches the second digital frame relatively well. The optimum blend point is then defined as a sample in the subset of the extended frame. The subset of the extended frame which matches the second digital frame relatively well is determined using a minimum average magnitude difference function over the samples in the subset. The blend point in this aspect comprises the first sample of the subset. To generate the 15 concatenated waveform, the subset of the extended frame is combined with the second digital frame and concatenated with the beginning segment of the extended frame to produce the concatenate waveform.

20 The concatenated sequence is then converted to analog form, or other physical representation of the waveforms being blended.

25 According to another aspect, the present invention provides an apparatus for synthesizing speech in response to text. The system includes a translator, by which text is translated to a sequence of sound segment codes which identify diphones. Next, a decoder is applied to the sequence of sound segment codes to produce strings of digital frames which represent diphones for respective sound segment codes in the sequence. A concatenator is provided by which a first digital frame at the ending of an identified string of digital frames for a particular sound segment code in the sequence is concatenated with a second digital frame at the beginning of an identified string of digital 30 frames of an adjacent sound segment code in the sequence to produc a speech data sequence. The concatenating system includes a buffer

- 5 -

to store samples of the first and second digital frames. Software, or other processing resources, determine a blend point for the first and second digital frames and blend the first and second frames in response to the blend point to produce a concatenation of the first and second
5 sound segments. An audio transducer is coupled to the concatenating system to generate synthesized speech in response to the speech data sequence.

In one embodiment of the invention, the resources that determine the optimum blend point include computing resources that compute an
10 extended frame comprising a discontinuity smoothed concatenation of the first digital frame with a replica of the first digital frame. Further resources find a subset of the extended frame with a minimum average magnitude difference between the samples in the subset and in the second digital frame and define the optimum blend point as the first
15 sample in the subset. The blending resources include software or other computing resources that supply a first set of samples derived from the first digital frame and the blend point as a first segment of the digital sequence. Next, the second digital frame is combined with the subset of the extended frame, with emphasis on the subset of the extended
20 frame in a starting sample and emphasis on the second digital frame in an ending sample to produce a second segment of the digital sequence. The first segment and second segment are combined produce the speech data sequence.

According to yet further aspects of the present invention, the
25 text-to-speech apparatus includes a processing module for adjusting the pitch and duration of the identified strings of digital frames in the speech data sequence in response to the input text. Also, the decoder is based on a vector quantization technique which provides excellent quality compression with very small decoding resources required.

- 6 -

Other aspects and advantages of the present invention can be seen upon review of the figures, the detailed description, and the claims which follow.

BRIEF DESCRIPTION OF THE FIGURES

5 Fig. 1 is a block diagram of a generic hardware platform incorporating the text-to-speech system of the present invention.

Fig. 2 is a flow chart illustrating the basic text-to-speech routine according to the present invention.

10 Fig. 3 illustrates the format of diphone records according to one embodiment of the present invention.

Fig. 4 is a flow chart illustrating the encoder for speech data according to the present invention.

15 Fig. 5 is a graph discussed in reference to the estimation of pitch filter parameters in the encoder of Fig. 4.

Fig. 6 is a flow chart illustrating the full search used in the encoder of Fig. 4.

20 Fig. 7 is a flow chart illustrating a decoder for speech data according to the present invention.

Fig. 8 is a flow chart illustrating a technique for blending the beginning and ending of adjacent diphone records.

25 Fig. 9 consists of a set of graphs referred to in explanation of the blending technique of Fig. 8.

Fig. 10 is a graph illustrating a typical pitch versus time diagram for a sequence of frames of speech data.

Fig. 11 is a flow chart illustrating a technique for increasing the pitch period of a particular frame.

30 Fig. 12 is a set of graphs referred to in explanation of the technique of Fig. 11.

Fig. 13 is a flow chart illustrating a technique for decreasing the pitch period of a particular frame.

- 7 -

Fig. 14 is a set of graphs referred to in explanation of the technique of Fig. 13.

Fig. 15 is a flow chart illustrating a technique for inserting a pitch period between two frames in a sequence.

5 Fig. 16 is a set of graphs referred to in explanation of the technique of Fig. 15.

Fig. 17 is a flow chart illustrating a technique for deleting a pitch period in a sequence of frames.

10 Fig. 18 is a set of graphs referred to in explanation of the technique of Fig. 17.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

A detailed description of preferred embodiments of the present invention is provided with reference to the figures. Figs. 1 and 2 provide an overview of a system incorporating the present invention. Fig. 15 3 illustrates the basic manner in which diphone records are stored according to the present invention. Figs. 4-6 illustrate the encoding methods based on vector quantization of the present invention. Fig. 7 illustrates the decoding algorithm according to the present invention.

20 Figs. 8 and 9 illustrate a preferred technique for blending the beginning and ending of adjacent diphone records. Figs. 10-18 illustrate the techniques for controlling the pitch and duration of sounds in the text-to-speech system.

I. System Overview (Figs. 1-3)

25 Fig. 1 illustrates a basic microcomputer platform incorporating a text-to-speech system based on vector quantization according to the present invention. The platform includes a central processing unit 10 coupled to a host system bus 11. A keyboard 12 or other text input device is provided in the system. Also, a display system 13 is coupled to the host system bus. The host system also includes a non-volatile

- 8 -

storage system such as a disk drive 14. Further, the system includes host memory 15. The host memory includes text-to-speech (TTS) code, including encoded voice tables, buffers, and other host memory. The text-to-speech code is used to generate speech data for supply to an 5 audio output module 16 which includes a speaker 17. The code also includes an optimum blend point, diphone concatenation routine as described in detail with reference to Figs. 8 and 9.

According to the present invention, the encoded voice tables include a TTS dictionary which is used to translate text to a string of 10 diphones. Also included is a diphone table which translates the diphones to identified strings of quantization vectors. A quantization vector table is used for decoding the sound segment codes of the diphone table into the speech data for audio output. Also, the system may include a vector quantization table for encoding which is loaded into 15 the host memory 15 when necessary.

The platform illustrated in Fig. 1 represents any generic microcomputer system, including a Macintosh based system, an DOS based system, a UNIX based system or other types of microcomputers. The text-to-speech code and encoded voice tables according to the 20 present invention for decoding occupy a relatively small amount of host memory 15. For instance, a text-to-speech decoding system according to the present invention may be implemented which occupies less than 640 kilobytes of main memory, and yet produces high quality, natural sounding synthesized speech.

25 The basic algorithm executed by the text-to-speech code is illustrated in Fig. 2. The system first receives the input text (block 20). The input text is translated to diphone strings using the TTS dictionary (block 21). At the same time, the input text is analyzed to generate intonation control data, to control the pitch and duration of the diphones 30 making up the speech (block 22).

- 9 -

After the text has been translated to diphone strings, the diphone strings are decompressed to generate vector quantized data frames (block 23). After the vector quantized (VQ) data frames are produced, the beginnings and endings of adjacent diphones are blended to smooth 5 any discontinuities (block 24). Next, the duration and pitch of the diphone VQ data frames are adjusted in response to the intonation control data (block 25 and 26). Finally, the speech data is supplied to the audio output system for real time speech production (block 27). For systems having sufficient processing power, an adaptive post filter may 10 be applied to further improve the speech quality.

The TTS dictionary can be implemented using any one of a variety of techniques known in the art. According to the present invention, diphone records are implemented as shown in Fig. 3 in a highly compressed format.

15 As shown in Fig. 3, records for a left diphone 30 and a record for a right diphone 31 are shown. The record for the left diphone 30 includes a count 32 of the number NL of pitch periods in the diphone. Next, a pointer 33 is included which points to a table of length NL 20 storing the number LP_i for each pitch period, i goes from 0 to NL-1 of pitch values for corresponding compressed frame records. Finally, pointer 34 is included to a table 36 of ML vector quantized compressed speech records, each having a fixed set length of encoded frame size related to nominal pitch of the encoded speech for the left diphone. The nominal pitch is based upon the average number of samples for a given 25 pitch period for the speech data base.

A similar structure can be seen for the right diphone 31. Using vector quantization, a length of the compressed speech records is very short relative to the quality of the speech generated.

30 The format of the vector quantized speech records can be understood further with reference to the frame encoder routine and the frame decoder routine described below with reference to Figs. 4-7.

- 10 -

II. The Encoder/Decoder Routines (Figs. 4-7)

The encoder routine is illustrated in Fig. 4. The encoder accepts as input a frame s_n of speech data. In the preferred system, the speech samples are represented as 12 or 16 bit two's complement numbers, 5 sampled at 22,252 Hz. This data is divided into non-overlapping frames s_n having a length of N, where N is referred to as the frame size. The value of N depends on the nominal pitch of the speech data. If the nominal pitch of the recorded speech is less than 165 samples (or 135 Hz), the value of N is chosen to be 96. Otherwise a frame size of 160 10 is used. The encoder transforms the N-point data sequence s_n into a byte stream of shorter length, which depends on the desired compression rate. For example, if N=160 and very high data compression is desired, the output byte stream can be as short as 12 eight bit bytes. A block diagram of the encoder is shown in Fig. 4.

15 Thus, the routine begins by accepting a frame s_n (block 50). To remove low frequency noise, such as DC or 60 Hz power line noise, and produce offset free speech data, signal s_n is passed through a high pass filter. A difference equation used in a preferred system to accomplish this is set out in Equation 1 for $0 \leq n < N$.

$$20 \quad x_n = s_n - s_{n-1} + 0.999 * x_{n-1}$$

Equation 1

The value x_n is the "offset free" signal. The variables s_{-1} and x_{-1} are initialized to zero for each diphone and are subsequently updated using the relation of Equation 2.

$$25 \quad x_{-1} = x_N \text{ and } s_{-1} = s_N$$

Equation 2

This step can be referred to as offset compensation or DC removal (block 51).

30 In order to partially decorrelate the speech samples and the quantization noise, the sequence x_n is passed through a fixed first order

- 11 -

linear prediction filter. The difference equation to accomplish this is set forth in Equation 3.

$$y_n = x_n - 0.875 * x_{n-1}$$

Equation 3

5 The linear prediction filtering of Equation 3 produces a frame y_n (block 52). The filter parameter, which is equal to 0.875 in Equation 3, will have to be modified if a different speech sampling rate is used. The value of x_{-1} is initialized to zero for each diphone, but will be updated in the step of inverse linear prediction filtering (block 60) as described
10 below.

It is possible to use a variety of filter types, including, for instance, an adaptive filter in which the filter parameters are dependent on the diphones to be encoded, or higher order filters.

15 The sequence y_n produced by Equation 3 is then utilized to determine an optimum pitch value, P_{opt} , and an associated gain factor, β . P_{opt} is computed using the functions $s_{xy}(P)$, $s_{xx}(P)$, $s_{yy}(P)$, and the coherence function $Coh(P)$ defined by Equations 4, 5, 6 and 7 as set out below.

$$20 s_{xy}(P) = \sum_{n=0}^{N-1} y_n * PBUF_{P_{max} - P + n}$$

Equation 4

$$25 s_{xx}(P) = \sum_{n=0}^{N-1} y_n * y_n$$

Equation 5

$$s_{yy}(P) = \sum_{N=0}^{N-1} PBUF_{P_{max} - P + n} * PBUF_{P_{max} - P + n}$$

30 and
Equation 6

- 12 -

$$\text{Coh}(P) = s_{xy}(P) * s_{xy}(P) / (s_{xx}(P) * s_{yy}(P))$$

Equation 7

PBUF is a pitch buffer of size P_{\max} , which is initialized to zero, and updated in the pitch buffer update block 59 as described below.

5 P_{opt} is the value of P for which $\text{Coh}(P)$ is maximum and $s_{xy}(P)$ is positive. The range of P considered depends on the nominal pitch of the speech being coded. The range is (96 to 350) if the frame size is equal to 96 and is (160 to 414) if the frame size is equal to 160. P_{\max} is 350 if nominal pitch is less than 160 and is equal to 414 otherwise.

10 The parameter P_{opt} can be represented using 8 bits.

The computation of P_{opt} can be understood with reference to Fig.

5. In Fig. 5, the buffer PBUF is represented by the sequence 100 and the frame y_n is represented by the sequence 101. In a segment of speech data in which the preceding frames are substantially equal to the frame y_n , PBUF and y_n will look as shown in Fig. 5. P_{opt} will have the value at point 102, where the vector y_n 101 matches as closely as possible a corresponding segment of similar length in PBUF 100.

The pitch filter gain parameter β is determined using the expression of Equation 8.

20
$$\beta = s_{xy}(P_{\text{opt}}) / s_{yy}(P_{\text{opt}}).$$

Equation 8

β is quantized to four bits, so that the quantized value of β can range from 1/16 to 1, in steps of 1/16.

25 Next, a pitch filter is applied (block 54). The long term correlations in the pre-emphasized speech data y_n are removed using the relation of Equation 9.

$$r_n = y_n - \beta * \text{PBUF}_{P_{\max} - P_{\text{opt}} + n}, \quad 0 \leq n < N.$$

Equation 9

This results in computation of a residual signal r_n .

- 13 -

Next, a scaling parameter G is generated using a block gain estimation routine (block 55). In order to increase the computational accuracy of the following stages of processing, the residual signal r_n is rescaled. The scaling parameter, G, is obtained by first determining the 5 largest magnitude of the signal r_n and quantizing it using a 7-level quantizer. The parameter G can take one of the following 7 values: 256, 512, 1024, 2048, 4096, 8192, and 16384. The consequence of choosing these quantization levels is that the rescaling operation can be implemented using only shift operations.

10 Next the routine proceeds to residual coding using a full search vector quantization code (block 56). In order to code the residual signal r_n , the n point sequence r_n is divided into non-overlapping blocks of length M, where M is referred to as the "vector size". Thus, M sample 15 blocks b_{ij} are created, where i is an index from zero to M-1 on the block number, and j is an index from zero to $N/M-1$ on the sample within the block. Each block may be defined as set out in Equation 10.

$$b_{ij} = r_{Mi+j}, (0 \leq i < N/M \text{ and } j \leq 0 < M)$$

Equation 10

20 Each of these M sample blocks b_{ij} will be coded into an 8 bit number using vector quantization. The value of M depends on the desired compression ratio. For example, with M equal to 16, very high compression is achieved (i.e., 16 residual samples are coded using only 8 bits). However, the decoded speech quality can be perceived to be somewhat noisy with M=16. On the other hand, with M=2, the 25 decompressed speech quality will be very close to that of uncompressed speech. However the length of the compressed speech records will be longer. The preferred implementation, the value M can take values 2, 4, 8, and 16.

30 The vector quantization is performed as shown in Fig. 6. Thus, for all blocks b_{ij} a sequence of quantization vectors is identified (block

- 14 -

120). First, the components of block b_{ij} are passed through a noise shaping filter and scaled as set out in Equation 11 (block 121).

$$w_j = 0.875 * w_{j-1} - 0.5 * w_{j-2} + 0.4375 * w_{j-3} + b_{ij}$$

$$0 \leq j < M$$

5 $v_{ij} = G * w_j$ $0 \leq j < M$

Equation 11

Thus, v_{ij} is the j th component of the vector v_i , and the values w_1 , w_{-2} and w_{-3} are the states of the noise shaping filter and are initialized to zero for each diphone. The filter coefficients are chosen to shape the quantization noise spectra in order to improve the subjective quality of the decompressed speech. After each vector is coded and decoded, these states are updated as described below with reference to blocks 124-126.

15 Next, the routine finds a pointer to the best match in a vector quantization table (block 122). The vector quantization table 123 consists of a sequence of vectors C_0 through C_{255} (block 123).

20 Thus, the vector v_i is compared against 256 M -point vectors, which are precomputed and stored in the code table 123. The vector C_{qi} which is closest to v_i is determined according to Equation 12. The value C_p for $p=0$ through 255 represents the p^{th} encoding vector from the vector quantization code table 123.

$$25 \min_p \sum_{j=0}^{M-1} (v_{ij} - C_{pj})^2$$

Equation 12

The closest vector C_{qi} can also be determined efficiently using the technique of Equation 13.

$$v_i^T \cdot C_{qi} \leq v_i^T \cdot C_p \text{ for all } p (0 \leq p \leq 255)$$

Equation 13

- 15 -

In Equation 13, the value v^T represents the transpose of the vector v , and " \bullet " represents the inner product operation in the inequality.

The encoding vectors C_p in table 123 are utilized to match on the noise filtered value v_{ij} . However in decoding, a decoding vector table 125 is used which consists of a sequence of vectors QV_p . The values QV_p are selected for the purpose of achieving quality sound data using the vector quantization technique. Thus, after finding the vector C_{qi} , the pointer q is utilized to access the vector QV_{qi} . The decoded samples corresponding to the vector b_i which is produced at step 55 of Fig. 4, is the M-point vector $(1/G) * QV_{qi}$. The vector C_p is related to the vector QV_p by the noise shaping filter operation of Equation 11. Thus, when the decoding vector QV_p is accessed, no inverse noise shaping filter needs to be computed in the decode operation. The table 125 of Fig. 6 thus includes noise compensated quantization vectors.

In continuing to compute the encoding vectors for the vectors b_{ij} which make up the residual signal r_n , the decoding vector of the pointer to the vector b_i is accessed (block 124). That decoding vector is used for filter and PBUF updates (block 126).

For the noise shaping filter, after the decoded samples are computed for each sub-block b_i , the error vector $(b_i - QV_{qi})$ is passed through the noise shaping filter as shown in Equation 14.

$$W_j = 0.875 * W_{j-1} - 0.5 * W_{j-2} + 0.4375 * W_{j-3} + [b_{ij} - QV_{qi}(j)]$$

$$0 \leq j < M$$

25 Equation 14

In Equation 14, the value $QV_{qi}(j)$ represents the j^{th} component of the decoding vector QV_{qi} . The noise shaping filter states for the next block are updated as shown in Equation 15.

$$w_{-1} = w_{M-1}$$

$$w_{-2} = w_{M-2}$$

- 16 -

$$w_{-3} = w_{M-3}$$

Equation 15

This coding and decoding is performed for all of the N/M sub-blocks to obtain N/M indices to the decoding vector table 125. This 5 string of indices Q_n , for n going from zero to $N/M-1$ represent identifiers for a string of decoding vectors for the residual signal r_n .

Thus, four parameters represent the N-point data sequence y_n :

- 1) Optimum pitch, P_{opt} (8 bits),
- 2) Pitch filter gain, β (4 bits),
- 10 3) Scaling parameter, G (3 bits), and
- 4) A string of decoding table indices, Q_n ($0 \leq n < N/M$).

The parameters β and G can be coded into a single byte. Thus, only (N/M) plus 2 bytes are used to represent N samples of speech. For example, suppose nominal pitch is 100 samples long, and $M=16$. In 15 this case, a frame of 96 samples of speech are represented by 8 bytes:

1 byte for P_{opt} , 1 byte for β and G , and 6 bytes for the decoding table indices Q_n . If the uncompressed speech consists of 16 bit samples, then this represents a compression of 24:1.

Back to Fig. 4, four parameters identifying the speech data are 20 stored (block 57). In a preferred system, they are stored in a structure as described with respect to Fig. 3 where the structure of the frame can be characterized as follows:

```
#define NumOfVectorsPerFrame (FrameSize / VectorSize)

25 struct frame {
    unsigned Gain : 4;
    unsigned Beta : 3;
    unsigned UnusedBit: 1;
    unsigned char Pitch ;
    unsigned char VQcodes[NumOfVectorsPerFrame]; };
```

- 17 -

The diphone record of Fig. 3 utilizing this frame structure can be characterized as follows:

```

DiphoneRecord
{
5      char LeftPhone, RightPhone;
      short LeftPitchPeriodCount, RightPitchPeriodCount;
      short *LeftPeriods, *RightPeriods;
      struct      frame *LeftData, *RightData;
}

```

10 These stored parameters uniquely provide for identification of the diphones required for text-to-speech synthesis.

15 As mentioned above with respect to Fig. 6, the encoder continues decoding the data being encoded in order to update the filter and PBUF values. The first step involved in this is an inverse pitch filter (block 58). With the vector r'_n corresponding to the decoded signal formed by concatenating the string of decoding vectors to represent the residual signal r'_n , the inverse filter is implemented as set out in Equation 16.

$$y'_n = r'_n + \beta * PBUF_{Pmax - Popt + n} \quad 0 \leq n < N. \quad \text{Equation 16}$$

20 Next, the pitch buffer is updated (block 59) with the output of the inverse pitch filter. The pitch buffer PBUF is updated as set out in Equation 17.

$$PBUF_n = PBUF_{(n + N)} \quad 0 \leq n < (P_{max} - N)$$

$$PBUF_{(Pmax - N + n)} = y'_n \quad 0 \leq n < N$$

25 Equation 17

Finally, the linear prediction filter parameters are updated using an inverse linear prediction filter step (block 60). The output of the inverse pitch filter is passed through a first order inverse linear prediction filter to obtain the decoded speech. The difference equation to implement this filter is set out in Equation 18.

$$x'_n = 0.875 * x'_{n-1} + y'_n$$

30 Equation 18

- 18 -

In Equation 18, x'_n is the decompressed speech. From this, the value of x'_{-1} for the next frame is set to the value x_N for use in the step of block 52.

5 Fig. 7 illustrates the decoder routine. The decoder module accepts as input $(N/M) + 2$ bytes of data, generated by the encoder module, and applies as output N samples of speech. The value of N depends on the nominal pitch of the speech data and the value of M depends on the desired compression ratio.

10 In software only text-to-speech systems, the computational complexity of the decoder must be as small as possible to ensure that the text-to-speech system can run in real time even on slow computers. A block diagram of the encoder is shown in Fig. 7.

15 The routine starts by accepting diphone records at block 200. The first step involves parsing the parameters G , β , P_{opt} and the vector quantization string Q_n (block 201). Next, the residual signal r'_n is decoded (block 202). This involves accessing and concatenating the decoding vectors for the vector quantization string as shown schematically at block 203 with access to the decoding vector table 125.

20 After the residual signal r'_n is decoded, an inverse pitch filter is applied (block 204). This inverse pitch filter is implemented as shown in Equation 19:

$$y'_n = r'_n + \beta * SPBUF(P_{max} - P_{opt} + n), \quad 0 \leq n < N.$$

Equation 19

25 SPBUF is a synthesizer pitch buffer of length P_{max} initialized as zero for each diphone, as described above with respect to the encoder pitch buffer PBUF.

For each frame, the synthesis pitch buffer is updated (block 205). The manner in which it is updated is shown in Equation 20:

$$SPBUF_n = SPBUF_{(n + N)} \quad 0 \leq n < (P_{max} - N)$$

$$SPBUF_{(P_{max} - N + n)} = y'_n \quad 0 \leq n < N$$

- 19 -

Equation 20

After updating SPBUF, the sequence y'_n is applied to an inverse linear prediction filtering step (block 206). Thus, the output of the inverse pitch filter y'_n is passed through a first order inverse linear prediction filter to obtain the decoded speech. The difference equation to implement the inverse linear prediction filter is set out in Equation 21:

$$x'_n = 0.875 * x'_{n-1} + y'_n$$

Equation 21

In Equation 21, the vector x'_n corresponds to the decompressed speech. This filtering operation can be implemented using simple shift operations without requiring any multiplication. Therefore, it executes very quickly and utilizes a very small amount of the host computer resources.

Encoding and decoding speech according to the algorithms described above, provide several advantages over prior art systems. First, this technique offers higher speech compression rates with decoders simple enough to be used in the implementation of software only text-to-speech systems on computer systems with low processing power. Second, the technique offers a very flexible trade-off between the compression ratio and synthesizer speech quality. A high-end computer system can opt for higher quality synthesized speech at the expense of a bigger RAM memory requirement.

III. Waveform Blending For Discontinuity Smoothing (Figs. 8 and 9)

As mentioned above with respect to Fig. 2, the synthesized frames of speech data generated using the vector quantization technique may result in slight discontinuities between diphones in a text string. Thus, the text-to-speech system provides a module for blending the diphone data frames to smooth such discontinuities. The blending technique of the preferred embodiment is shown with respect to Figs. 8 and 9.

- 20 -

Two concatenated diphones will have an ending frame and a beginning frame. The ending frame of the left diphone must be blended with the beginning frame of the right diphone without audible discontinuities or clicks being generated. Since the right boundary of 5 the first diphone and the left boundary of the second diphone correspond to the same phoneme in most situations, they are expected to be similar looking at the point of concatenation. However, because the two diphone codings are extracted from different context, they will not look identical. This blending technique is applied to eliminate 10 discontinuities at the point of concatenation. In Fig. 9, the last frame, referring here to one pitch period, of the left diphone is designated L_n ($0 \leq n < PL$) at the top of the page. The first frame (pitch period) of the right diphone is designated R_n ($0 \leq n < PR$). The blending of L_n and R_n according to the present invention will alter these two pitch periods only 15 and is performed as discussed with reference to Fig. 8. The waveforms in Fig. 9 are chosen to illustrate the algorithm, and may not be representative of real speech data.

Thus, the algorithm as shown in Fig. 8 begins with receiving the 20 left and right diphone in a sequence (block 300). Next, the last frame of the left diphone is stored in the buffer L_n (block 301). Also, the first frame of the right diphone is stored in buffer R_n (block 302).

Next, the algorithm replicates and concatenates the left frame L_n 25 to form extend frame (block 303). In the next step, the discontinuities in the extended frame between the replicated left frames are smoothed (block 304). This smoothed and extended left frame is referred to as E_L_n in Fig. 9.

- 21 -

The extended sequence El_n ($0 \leq n < PL$) is obtained in the first step as shown in Equation 22:

$$\begin{aligned} El_n &= L_n & n &= 0, 1, \dots, PL-1 \\ El_{PL+n} &= L_n & n &= 0, 1, \dots, PL-1 \end{aligned}$$

5

Equation 22

Then discontinuity smoothing from the point $n = PL$ is conducted according to the filter of Equation 23:

$$El_{PL+n} = El_{PL+n} + [El_{(PL-1)} - El'_{(PL-1)}] * \Delta^{n+1},$$

$$n = 0, 1, \dots, (PL/2).$$

10

Equation 23

In Equation 23, the value Δ is equal to $15/16$ and $El'_{(PL-1)} = El_2 + 3 * (El_1 - El_0)$. Thus, as indicated in Fig. 9, the extended sequence El_n is substantially equal to L_n on the left hand side, has a smoothed region beginning at the point PL and converges on the original shape of L_n toward the point $2PL$. If L_n was perfectly periodic, then $El_{PL-1} = El'_{PL-1}$.

In the next step, the optimum match of R_n with the vector El_n is found. This match point is referred to as P_{opt} . (Block 305.) This is accomplished essentially as shown in Fig. 9 by comparing R_n with El_n to find the section of El_n which most closely matches R_n . This optimum blend point determination is performed using Equation 23 where W is the minimum of PL and PR , and $AMDF$ represents the average magnitude difference function.

W-1

$$25 \quad AMDF(p) = \sum_{n=0}^{W-1} | El_{n+p} - R_n |$$

Equation 24

This function is computed for values of p in the range of 0 to $PL-1$.

1. The vertical bars in the operation denote the absolute value. W is the window size for the $AMDF$ computation. P_{opt} is chosen to be the value at which $AMDF(p)$ is minimum. This means that $p = P_{opt}$

30

- 22 -

corresponds to the point at which sequences EI_{n+p} ($0 \leq n < W$) and R_n ($0 \leq n < W$) are very close to each other.

5 After determining the optimum blend point P_{opt} , the waveforms are blended (block 306). The blending utilizes a first weighting ramp WL which is shown in Fig. 9 beginning at P_{opt} in the EI_n trace. In a second ramp, WR is shown in Fig. 9 at the R_n trace which is lined up with P_{opt} . Thus, in the beginning of the blending operation, the value of EI_n is emphasized. At the end of the blending operation, the value of R_n is emphasized.

10 Before blending, the length PL of L_n is altered as needed to ensure that when the modified L_n and R_n are concatenated, the waveforms are as continuous as possible. Thus, the length $P'L$ is set to P_{opt} if P_{opt} is greater than $PL/2$. Otherwise, the length $P'L$ is equal to $W + P_{opt}$ and the sequence L_n is equal to EI_n for $0 \leq n \leq (P'L-1)$.

15 The blending ramp beginning at P_{opt} is set out in Equation 25:

$$R_n = EI_{n+P_{opt}} + (R_n - EI_{n+P_{opt}}) * (n+1)/W \quad 0 \leq n < W$$

$$R_n = R_n \quad W \leq n < PR$$

Equation 25

20 Thus, the sequences L_n and R_n are windowed and added to get the blended R_n . The beginning of L_n and the ending of R_n are preserved to prevent any discontinuities with adjacent frames.

This blending technique is believed to minimize blending noise in synthesized speech produced by any concatenated speech synthesis.

IV. Pitch and Duration Modification (Figs. 10-18)

25 As mentioned above with respect to Fig. 2, a text analysis program analyzes the text and determines the duration and pitch contour of each phone that needs to be synthesized and generates intonation control signals. A typical control for a phone will indicate that a given

- 23 -

phoneme, such as AE, should have a duration of 200 milliseconds and a pitch should rise linearly from 220Hz to 300Hz. This requirement is graphically shown in Fig. 10. As shown in Fig. 10, T equals the desired duration (e.g. 200 milliseconds) of the phoneme. The frequency f_b is the desired beginning pitch in Hz. The frequency f_e is the desired ending pitch in Hz. The labels P_1, P_2, \dots, P_6 indicate the number of samples of each frame to achieve the desired pitch frequencies f_b, f_2, \dots, f_6 . The relationship between the desired number of samples, P_i , and the desired pitch frequency f_i ($f_1 = f_b$), is defined by the relation:

10 $P_i = F_s / f_i$, where F_s is the sampling frequency for the data.

As can be seen in Fig. 10, the pitch period for a lower frequency period of the phoneme is longer than the pitch period for a higher frequency period of the phoneme. If the nominal frequency were P_3 , then the algorithm would be required to lengthen the pitch period for frames P_1 and P_2 and decrease the pitch periods for frames P_4, P_5 and P_6 . Also, the given duration T of the phoneme will indicate how many pitch periods should be inserted or deleted from the encoded phoneme to achieve the desired duration period. Figs. 11 through 18 illustrate a preferred implementation of such algorithms.

20 Fig. 11 illustrates an algorithm for increasing the pitch period, with reference to the graphs of Fig. 12. The algorithm begins by receiving a control to increase the pitch period to $N + \Delta$, where N is the pitch period of the encoded frame. (Block 350). In the next step, the pitch period data is stored in a buffer x_n (block 351). x_n is shown in Fig. 12 at the top of the page. In the next step, a left vector L_n is generated by applying a weighting function WL to the pitch period data x_n with reference to Δ (block 352). This weighting function is illustrated in Equation 26 where $M = N - \Delta$:

$$L_n = x_n \quad \text{for } 0 \leq n < \Delta$$

30 $L_n = x_n * (N-n)/(M+1) \quad \text{for } \Delta \leq n < N$

- 24 -

Equation 26

As can be seen in Fig. 12, the weighting function WL is constant from the first sample to sample Δ , and decreases from Δ to N.

5 Next, a weighting function WR is applied to x_n (block 353) as can be seen in the Fig. 12. This weighting function is executed as shown in Equation 27:

$$\begin{aligned} R_n &= x_{n+\Delta} * (n+1)/(M+1) && \text{for } 0 \leq n < N-\Delta \\ R_n &= x_{n+\Delta} && \text{for } N-\Delta \leq n < N. \end{aligned}$$

Equation 27

10 As can be seen in Fig. 12, the weighting function WR increases from 0 to $N-\Delta$ and remains constant from $N-\Delta$ to N. The resulting waveforms L_n and R_n are shown conceptually in Fig. 12. As can be seen, L_n maintains the beginning of the sequence x_n , while R_n maintains the ending of the data x_n .

15 The pitch modified sequence y_n is formed (block 354) by adding the two sequences as shown in Equation 28:

$$y_n = L_n + R_{(n-\Delta)}$$

Equation 28

20 This is graphically shown in Fig. 12 by placing R_n shifted by Δ below L_n . The combination of L_n and R_n shifted by Δ is shown to be y_n at the bottom of Fig. 12. The pitch period for y_n is $N+\Delta$. The beginning of y_n is the same as the beginning of x_n , and the ending of y_n is substantially the same as the ending of x_n . This maintains continuity with adjacent frames in the sequence, and accomplishes a smooth transition while extending the pitch period of the data.

25 Equation 28 is executed with the assumption that L_n is 0, for $n \leq N$, and R_n is 0 for $n < 0$. This is illustrated pictorially in Fig. 12.

- 25 -

An efficient implementation of this scheme which requires at most one multiply per sample, is shown in Equation 29:

$$y_n = x_n \quad 0 \leq n < \Delta$$

$$y_n = x_n + [x_{n-\Delta} - x_n] * (n-\Delta + 1) / (N-\Delta + 1) \quad \Delta \leq n < N$$

5 $y_n = x_n - \Delta$
 $N \leq n < N_d$

Equation 29

This results in a new pitch period having a pitch period of $N + \Delta$.

10 There are also instances in which the pitch period must be decreased. The algorithm for decreasing the pitch period is shown in Fig. 13 with reference to the graphs of Fig. 14. Thus, the algorithm begins with a control signal indicating that the pitch period must be decreased to $N - \Delta$. (Block 400). The first step is to store two consecutive pitch periods in the buffer x_n (block 401). Thus, the buffer 15 x_n as can be seen in Fig. 14 consists of two consecutive pitch periods, with the period N_1 being the length of the first pitch period, and N_2 being the length of the second pitch period. Next, two sequences L_n and R_n are conceptually created using weighting functions WL and WR (blocks 402 and 403). The weighting function WL emphasizes the beginning of 20 the first pitch period, and the weighting function WR emphasizes the ending of the second pitch period. These functions can be conceptually represented as shown in Equations 30 and 31, respectively:

- 26 -

$$L_n = x_n \quad \text{for } 0 \leq n < N_l - W$$

$$L_n = x_n * (N_l - n) / (W + 1) \quad W \leq n < N_l$$

$$L_n = 0 \quad \text{otherwise.}$$

Equation 30

5 and

$$R_n = x_n * (n - N_l + W - \Delta + 1) / (W + 1) \quad \text{for } N_l - W + \Delta \leq n < N_l + \Delta$$

$$R_n = x_n \quad \text{for } N_l + \Delta \leq n < N_l + N_r$$

$$R_n = 0 \quad \text{otherwise.}$$

Equation 31

10 In these equations, Δ is equal to the difference between N_l and the desired pitch period N_d . The value W is equal to $2 * \Delta$, unless $2 * \Delta$ is greater than N_d , in which case W is equal to N_d .

15 These two sequences L_n and R_n are blended to form a pitch modified sequence y_n (block 404). The length of the pitch modified sequence y_n will be equal to the sum of the desired length and the length of the right phoneme frame N_r . It is formed by adding the two sequences as shown in Equation 32:

$$y_n = L_n + R_{(n + \Delta)}$$

Equation 32

20 Thus, when a pitch period is decreased, two consecutive pitch periods of data are affected, even though only the length of one pitch period is changed. This is done because pitch periods are divided at places where short-term energy is the lowest within a pitch period. Thus, this strategy affects only the low energy portion of the pitch periods. This minimizes the degradation in speech quality due to the pitch modification. It should be appreciated that the drawings in Fig. 14 are simplified and do not represent actual pitch period data.

- 27 -

An efficient implementation of this scheme, which requires at most one multiply per sample, is set out in Equations 33 and 34.

The first pitch period of length N_d is given by Equation 33:

$$y_n = x_n \quad 0 \leq n < N_l - W$$

5 $y_n = x_n + [x_{n+\Delta} - x_n] * (n - N_l + W + 1) / (W + 1) \quad N_l - W \leq n < N_d$

Equation 33

The second pitch period of length N_r is generated as shown in Equation 34:

$$y_n = x_{n-\Delta} + [x_n - x_{n-\Delta}] * (n - \Delta - N_l + W + 1) / (W + 1)$$

10 $N_l \leq n < N_l + \Delta$

$$y_n = x_n \quad N_l + \Delta \leq n < N_l + N_r$$

Equation 34

As can be seen in Fig. 14, the sequence L_n is essentially equal to the first pitch period until the point $N_l - W$. At that point, a decreasing ramp WL is applied to the signal to dampen the effect of the first pitch period.

As also can be seen, the weighting function WR begins at the point $N_l - W + \Delta$ and applies an increasing ramp to the sequence x_n until the point $N_l + \Delta$. From that point, a constant value is applied. This has the effect of damping the effect of the right sequence and emphasizing the left during the beginning of the weighting functions, and generating a ending segment which is substantially equal to the ending segment of x_n emphasizing the right sequence and damping the left. When the two functions are blended, the resulting waveform y_n is substantially equal to the beginning of x_n at the beginning of the sequence, at the point $N_l - W$ a modified sequence is generated until the point N_l . From N_l to the ending, sequence x_n shifted by Δ results.

- 28 -

A need also arises for insertion of pitch periods to increase the duration of a given sound. A pitch period is inserted according to the algorithm shown in Fig. 15 with reference to the drawings of Fig. 16.

5 The algorithm begins by receiving a control signal to insert a pitch period between frames L_n and R_n (block 450). Next, both L_n and R_n are stored in the buffer (block 451), where L_n and R_n are two adjacent pitch periods of a voice diphone. (Without loss of generality, it is assumed for the description that the two sequences are of equal lengths N.)

10 In order to insert a pitch period, x_n of the same duration, without causing a discontinuity between L_n and x_n and between x_n and R_n , the pitch period x_n should resemble R_n around $n=0$ (preserving L_n to x_n continuity), and should resemble L_n around $n=N$ (preserving x_n to R_n continuity). This is accomplished by defining x_n as shown in Equation 15 35:

$$x_n = R_n + (L_n - R_n) * [(n+1)/(N+1)] \quad 0 \leq n < N-1$$

Equation 35

20 Conceptually, as shown in Fig. 15, the algorithm proceeds by generating a left vector $WL(L_n)$, essentially applying to the increasing ramp WL to the signal L_n . (Block 452).

25 A right vector $WR(R_n)$ is generated using the weighting vector WR (block 453) which is essentially a decreasing ramp as shown in Fig. 16. Thus, the ending of L_n is emphasized with the left vector, and the beginning of R_n is emphasized with the vector WR .

Next, $WR(L_n)$ and $WR(R_n)$ are blended to create an inserted period x_n (block 454).

The computation requirement for inserting a pitch period is thus just a multiplication and two additions per speech sample.

Finally, concatenation of L_n , x_n and R_n produces a sequence with an inserted pitch period (block 455).

- 29 -

5 Deletion of a pitch period is accomplished as shown in Fig. 17 with reference to the graphs of Fig. 18. This algorithm, which is very similar to the algorithm for inserting a pitch period, begins with receiving a control signal indicating deletion of pitch period R_n which follows L_n (block 500). Next, the pitch periods L_n and R_n are stored in the buffer (block 501). This is pictorially illustrated in Fig. 18 at the top of the page. Again, without loss of generality, it is assumed that the two sequences have equal lengths N .

10 The algorithm operates to modify the pitch period L_n which precedes R_n (to be deleted) so that it resembles R_n , as n approaches N . This is done as set forth in Equation 36:

$$L'_n = L_n + (R_n - L_n) * [(n+1)/(N+1)] \quad 0 \leq n < N-1$$

Equation 36

15 In Equation 36, the resulting sequence L'_n is shown at the bottom of Fig. 18. Conceptually, Equation 36 applies a weighting function WL to the sequence L_n (block 502). This emphasizes the beginning of the sequence L_n as shown. Next, a right vector WR (R_n) is generated by applying a weighting vector WR to the sequence R_n that emphasizes the ending of R_n (block 503).

20 WL (L_n) and WR (R_n) are blended to create the resulting vector L'_n . (Block 504). Finally, the sequence $L_n - R_n$ is replaced with the sequence L'_n in the pitch period string. (Block 505).

IV. Conclusion

25 Accordingly, the present invention presents a software only text-to-speech system which is efficient, uses a very small amount of memory, and is portable to a wide variety of standard microcomputer platforms. It takes advantage of knowledge about speech data, and to create a speech compression, blending, and duration control routine which produces very high quality speech with very little computational resources.

- 30 -

A source code listing of the software for executing the compression and decompression, the blending, and the duration and pitch control routines is provided in the Appendix as an example of a preferred embodiment of the present invention.

5 The foregoing description of preferred embodiments of the present invention has been provided for the purposes of illustration and description. It is not intended to be exhaustive or to limit the invention to the precise forms disclosed. Obviously, many modifications and variations will be apparent to practitioners skilled in this art. The
10 embodiments were chosen and described in order to best explain the principles of the invention and its practical application, thereby enabling others skilled in the art to understand the invention for various embodiments and with various modifications as are suited to the particular use contemplated. It is intended that the scope of the
15 invention be defined by the following claims and their equivalents.

- 31 -

APPENDIX

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37 C.F.R. § 1.96(a)

COMPUTER PROGRAM LISTINGS

TABLE OF CONTENTS

<u>Section</u>	<u>Page</u>
I. <u>ENCODER MODULE</u>	33
II. <u>DECODER MODULE</u>	43
III. <u>BLENDING MODULE</u>	55
IV. <u>INTONATION ADJUSTMENT MODULE</u>	59

I. ENCODER MODULE

```
#include <stdio.h>
#include <math.h>
#include <StdLib.h>
#include <types.h>
#include <fcntl.h>
#include <string.h>

#include <types.h>
#include <files.h>
#include <resources.h>
#include <memory.h>
#include "vqcoder.h"

#define LAST_FRAME_FLAG 128
#define PBUF_SIZE 440
static float oc_state[2], nsf_state[NSF_ORDER + 1];
static short pstate[PORDER + 1], dstate[PORDER + 1];
static short AnaPbuf[PBUF_SIZE];

static short vsize, cbook_size, bs_size;

#pragma segment vqlib

/* Read Code Books */
float *EncodeBook[MAX_CBOOK_SIZE];
short *DecodeBook[MAX_CBOOK_SIZE];
get_cbook(short ratio)
{
    short *p;
    short frame_size, i;
    static short last_ratio = 0;

    Handle h;
    int skip;
    h = GetResource('CBOK', 1);
    HLock(h);
    p = (short *) *h;

    if (ratio == last_ratio)
        return;
    last_ratio = ratio;

    if (ratio < 3)
        return;

    if (NOMINAL_PITCH < 165)
```

- 33 -

```
    frame_size = 96;
else
    frame_size = 160;

get_compr_pars(ratio, frame_size, &vsize, &cbook_size, &bs_size);
skip = 0;
while (p[skip + 1] != vsize)
{
    short t1, t2;
    t2 = p[skip];
    t1 = p[skip + 1];
    skip += sizeof(float) * (2 * t2 - 1) * (t1 + 1) / sizeof(short)
           + (2 * t2 * t1 + 2);
}

/* Skip Binary search tree */
skip += sizeof(float) * (cbook_size - 1) * (vsize + 1) / sizeof(short)
       + (cbook_size * vsize + 2);

/* Get pointers to Full search code books */
for (i = 0; i < cbook_size; i++)
{
    EncodeBook[i] = (float *) &p[skip];
    skip += (vsize + 1) * sizeof(float) / sizeof(short);
}

for (i = 0; i < cbook_size; i++)
{
    DecodeBook[i] = p + skip;
    skip += vsize;
}

char *getcbook(long *len, short ratio)
{
    get_cbook(ratio);
    *len = sizeof(short) * vsize * cbook_size;
    /* plus one is to make space at the end for the array of pointers */
    return (char *) DecodeBook[0];
}

/* A Routine for Pitch filter parameter Estimation */
GetPitchFilterPars (x, len, pbuf, min_pitch, max_pitch, pitch, beta)
float *beta;
short *x, *pbuf;
short min_pitch, max_pitch;
short len;
unsigned int *pitch;
{
    /* Estimate long-term predictor */
```

- 34 -

```

int best_pitch, i, j;
float syy, sxy, best_sxy = 0.0, best_syy = 1.0;
short *ptr;

best_pitch = min_pitch;
ptr = pbuf + PBUF_SIZE - min_pitch;
syy = 1.0;
for (i = 0; i < len; i++)
{
    syy += (*ptr) * (*ptr);
    ptr++;
}
for (j = min_pitch; j < max_pitch; j++)
{
    sxy = 0.0;
    ptr = pbuf + PBUF_SIZE - j;
    for (i = 0; i < len; i++)
        sxy += x[i] * (*ptr++);

    if (sxy > 0 && (sxy * sxy * best_syy > best_sxy * best_sxy * syy))
    {
        best_syy = syy;
        best_sxy = sxy;
        best_pitch = j;
    }
    syy = syy - pbuf[PBUF_SIZE - j + len - 1] * pbuf[PBUF_SIZE - j + len - 1]
        + pbuf[PBUF_SIZE - j - 1] * pbuf[PBUF_SIZE - j - 1];
}
*pitch = best_pitch;
*beta = best_sxy / best_syy;
}

/* Quantization of LTP gain parameter */
CodePitchFilterGain(beta, bcode)
float beta;
unsigned int *bcode;
{
    int i;
    for (i = 0; i < DLB_TAB_SIZE; i++)
    {
        if (beta <= dlb_tab[i])
            break;
    }
    *bcode = i;
}

/* Pitch filter */
PitchFilter(data, len, pbuf, pitch, ibeta)
float *data;

```

- 35 -

```

short ibeta;
short *pbuf;
short len;
unsigned int pitch;
{

long pn;
int i, j;

j = PBUF_SIZE - pitch;
for (i = 0; i < len; i++)
{
    pn = ((ibeta * pbuf[j++]) >> 4);
    data[i] -= pn;
}
}

/* Forward Noise Shaping filter */
FNSFilter(float *inp, float *state, short len, float *out)
{
    short i, j;
    for (j = 0; j < len; j++)
    {
        float tmp = inp[j];
        for (i = 1; i <= NSF_ORDER; i++)
            tmp += state[i] * nsf[i];
        out[j] = state[0] = tmp;
        for (i = NSF_ORDER; i > 0; i--)
            state[i] = state[i-1];
    }
}

/* Update Noise shaping Filter states */
UpdateNSFState(float *inp, float *state, short len)
{
    short i, j;
    float temp_state[NSF_ORDER+1];

    for (i = 0; i <= NSF_ORDER; i++)
        temp_state[i] = 0;

    for (j = 0; j < len; j++)
    {
        float tmp = inp[j];
        for (i = 1; i <= NSF_ORDER; i++)
            tmp += temp_state[i] * nsf[i];
        temp_state[0] = tmp;
        for (i = NSF_ORDER; i > 0; i--)
            temp_state[i] = temp_state[i-1];
    }
}

```

- 36 -

```

        }

        for (i = 0; i <= NSF_ORDER; i++)
            state[i] = state[i] - temp_state[i];
    }

/* Quantization of Segment Power */
CodeBlockGain(power, gcode)
float power;
unsigned int *gcode;
{
    int i;
    for (i = 0; i < DLG_TAB_SIZE; i++)
    {
        if (power <= dlg_tab[i])
            break;
    }
    *gcode = i;
}

/* Full search Coder */
VQCoder(float *x, float *nsf_state, short len, struct frame *bs)
{
    float          max_x, tmp;
    int           i, j, k, index, lshift_count;
    unsigned int   gcode;
    float          min_err = 0;

    max_x = x[0];
    for (i = 1; i < len; i++)
        if (fabs(x[i]) > max_x)
            max_x = fabs(x[i]);

    CodeBlockGain(max_x, &gcode);
    max_x = qlg_tab[gcode];
    lshift_count = 7 - gcode;           /* To scale 14-bit Code book output to the 16-bit
actual value */
    bs->gcode = gcode;

    for (i = 0; i < len; i += vsize)
    {
        /* Filter the data vector */
        FNSFilter(&x[i], nsf_state, vsize, &x[i]);

        /* Scale data */
        for (j = i; j < i + vsize; j++)
            x[j] = x[j] * 1024 / max_x;

        index = 0;
        for (j = 0; j < cbook_size; j++)
        {

```

- 37 -

```

tmp = EncodeBook[j][vsize] * 1024.0;
for (k = 0; k < vsize; k++)
    tmp -= x[i+k] * EncodeBook[j][k];

if (tmp < min_err || j == 0)
{
    index = j;
    min_err = tmp;
}
}
bs->vqcode[i/vsize] = index;

/* Rescale data: Decoded data is 14-bits, convert to 16 bits */
if (lshift_count)
{
    for (k = 0; k < vsize; k++)
        x[i+k] = ((4 * DecodeBook[index][k]) >> lshift_count);
}
else
{
    for (k = 0; k < vsize; k++)
        x[i+k] = 4 * DecodeBook[index][k];
}

/* Update noise shaping filter state */
UpdateNSFState(&x[i], nsf_state, vsize);
}

init_compress()
{
    int i;
    oc_state[0] = 0;;
    oc_state[1] = 0;;
    for (i = 0; i <= PORDER; i++)
        pstate[i] = dstate[i] = 0;
    for (i = 0; i < PBUF_SIZE; i++)
        AnaPbuf[i] = 0;
    for (i=0; i <= NSF_ORDER; i++)
        nsf_state[i] = 0;
}

Encoder(xn, frame_size, min_pitch, max_pitch, bs)
short xn[];
struct frame *bs;
short frame_size, min_pitch, max_pitch;
{
    unsigned int pitch, bcode;
    float    preemp_xn[PBUF_SIZE], beta;
    short    xn_copy[PBUF_SIZE];
}

```

- 38 -

```

short    ibeta;
float    acc;
int i, j;

/* Offset Compensation */
for (i = 0; i < frame_size; i++)
{
    float inp = xn[i];
    xn[i] = inp - oc_state[0] + ALPHA * oc_state[1];
    oc_state[1] = xn[i];
    oc_state[0] = inp;
}

/* Linear Prediction Filtering */
for (i = 0; i < frame_size; i++)
{
    acc = pstate[0] = xn[i];
    for (j = 1; j <= PORDER; j++)
        acc -= pstate[j] * pfilt[j];
    xn_copy[i] = preemp_xn[i] = acc;
    for (j = PORDER; j > 0; j--)
        pstate[j] = pstate[j-1];
}

GetPitchFilterPars (xn_copy, frame_size, AnaPbuf, min_pitch,
    max_pitch, &pitch, &beta);
CodePitchFilterGain(beta, &bcode);
ibeta = qlb_tab[bcode];

bs->bcode = bcode;
bs->pitch = pitch - min_pitch + 1;

PitchFilter(preemp_xn, frame_size, AnaPbuf, pitch, ibeta);

VQCoder(preemp_xn, nsf_state, frame_size, bs);

/* Inverse Filtering */
j = PBUF_SIZE - pitch;
for (i = 0; i < frame_size; i++)
{
    xn_copy[i] = preemp_xn[i];
    xn_copy[i] += ((ibeta * AnaPbuf[j + 1]) >> 4);
}

/* Update Pitch Buffer */
j = 0;
for (i = frame_size; i < PBUF_SIZE; i++)
    AnaPbuf[j + 1] = AnaPbuf[i];
for (i = 0; i < frame_size; i++)

```

- 39 -

```

AnaPbuf[j+] = xn_copy[i];

/* Inverse LP filtering */
for (i = 0; i < frame_size; i++)
{
    acc = xn_copy[i];
    for (j = 1; j <= PORDER; j++)
        acc = acc + dstate[j] * pfilt[j];
    dstate[0] = acc;
    for (j = PORDER; j > 0; j--)
        dstate[j] = dstate[j-1];
}

for (j = 0; j <= PORDER; j++)
    pstate[j] = dstate[j];
}

compress (short *input, short ilen, unsigned char *output, long *olen, long docomp)
{
    int          i, j, vcount;
    unsigned char temp;
    short         frame_size, min_pitch, max_pitch;

    if (docomp > 2)
    {
        init_compress();

        if (NOMINAL_PITCH < 165)
        {
            min_pitch = 96;
            frame_size = 96;
            max_pitch = 350;
        }
        else
        {
            min_pitch = 160;
            frame_size = 160;
            max_pitch = 414;
        }

        bs_size = frame_size / vsize + 2;
        /* TEMPORARY: Storing State information */
        pstate[1] = *(input - 1);
        if (pstate[1] > 0)
            pstate[1] = (pstate[1] + 128) / 256 + 128;
        else
            pstate[1] = (pstate[1] - 128) / 256 + 128;

        if (pstate[1] < 0)
            pstate[1] = 0;
    }
}

```

- 40 -

```
if (pstate[1] > 255)
    pstate[1] = 255;
*output = pstate[1];
j = 1;
pstate[1] = pstate[1] - 128;
pstate[1] = 256 * pstate[1];
dstate[1] = pstate[1];
/* End of Hack */
for (i = 0; i < ilen; i += frame_size)
{
    Encoder(input+i, frame_size, min_pitch, max_pitch, output+j);
    j += bs_size;
}
j -= bs_size;

/* Number of vectors in last frame */
vcount = (ilen + frame_size - i + vsize - 1) / vsize;
temp = output[j];
output[j] = vcount + LAST_FRAME_FLAG;
output[j + vcount + 2] = temp;
*olen = j + vcount + 3;
}
else
{
    static long SampCount = 0;
    copy(input, output, 2*ilen);
    SampCount += ilen;
    *olen = ilen;
}
}

copy(a, b, len)
short *a, *b;
short len;
{
    int i;
    for (i = 0; i < len; i++)
        *b++ = (*a++);
}
```

- 41 -

II. DECODER MODULE

```

#include <Types.h>
#include <Memory.h>
#include <Quickdraw.h>
#include <ToolUtils.h>
#include <errors.h>
#include <files.h>

#include "vtcint.h"
#include <stdlib.h>
#include <math.h>
#include <sysequ.h>
#include <string.h>

#define MAX_CBOOK_SIZE 256
#define LAST_FRAME_FLAG 128
#define PORDER 1
#define IPCONS 7 /* 7/8 */
#define LARGE_NUM 100000000
#define VOICED 1

#define LEFT 0
#define RIGHT 1
#define UNVOICED 0

#define PFILT_ORDER 8

struct frame {
    unsigned gcode : 4;
    unsigned bcode : 4;
    unsigned pitch : 8;
    unsigned char vqcode[];
};

void expand(short **DecodeBook, short frame_size, short vsize,
           short min_pitch, struct frame *bs, short *output, short smpnum);

get_compr_pars(short ratio, short frame_size, short *vsize,
               short *cbook_size, short *bs_size)
{
    switch (ratio)
    {
        case 4:
            *vsize = 2;
            *cbook_size = 256;
            *bs_size = frame_size/2 + 2;
            break;
    }
}

```

- 42 -

```

case 7:
    *vsize = 4;
    *cbook_size = 256;
    *bs_size = frame_size/4 + 2;
    break;
case 14:
    *vsize = 8;
    *cbook_size = 256;
    *bs_size = frame_size/8 + 2;
    break;
case 24:
    *vsize = 16;
    *cbook_size = 256;
    *bs_size = frame_size/16 + 2;
    break;
default:
    *vsize = 2;
    *cbook_size = 256;
    *bs_size = frame_size/2 + 2;
    break;
}
}

short *SnInit(short comp_ratio)
{
    short *state, *ptr;
    int i;

    state = ptr = (short *)NewPtr((PFILT_ORDER+1 + PFILT_ORDER/2 + 2) *
sizeof(short));
    if ( state == nil )
    {
        return nil;
    }
    for (i=0;i<PFILT_ORDER+1;i++)
        *ptr++ = 0;
/*
    if (comp_ratio == 24)
    {
        *ptr++ = 0.036953 * 32768 + 0.5;
        *ptr++ = -0.132232 * 32768 - 0.5;
        *ptr++ = 0.047798 * 32768 + 0.5;
        *ptr++ = 0.403220 * 32768 + 0.5;
        *ptr++ = 0.290033 * 32768 + 0.5;
    }
    else
    {
        *ptr++ = 0.074539 * 32768 + 0.5;
        *ptr++ = -0.174290 * 32768 - 0.5;
        *ptr++ = 0.013704 * 32768 + 0.5;
    }
}

```

- 43 -

```

        *ptr++ = 0.426815 * 32768 + 0.5;
        *ptr++ = 0.320707 * 32768 + 0.5;
    }
}

if (comp_ratio == 24)
{
    *ptr++ = 1211;
    *ptr++ = -4333;
    *ptr++ = 1566;
    *ptr++ = 13213;
    *ptr++ = 9504;
}
else
{
    *ptr++ = 2442;
    *ptr++ = -5711;
    *ptr++ = 449;
    *ptr++ = 13986;
    *ptr++ = 10509;
}
*ptr = 0; /* DC value */
return state;
}

SnDone(char *state)
{
    if (state != nil)
    {
        DisposPtr(state);
    }
}

short **SnDelInit(p, ratio, frame_size)
short *p, ratio, frame_size;
{
    int i;
    short cbook_size = 256, vsize = 16, bs_size;
    short **DecodeBook;

    get_compr_pars(ratio, frame_size, &vsize, &cbook_size, &bs_size);

    DecodeBook = (short**)NewPtr(cbook_size * sizeof(short*));
    if (DecodeBook) {
        for (i = 0; i < cbook_size; i++)
        {
            DecodeBook[i] = p;
            p += vsize;
        }
    }
    return DecodeBook;
}

```

- 44 -

```

}

SnDeDone(char *DecodeBook)
{
    if ( DecodeBook != nil )
    {
        DisposPtr(DecodeBook);
    }
}

void
expand(short **DecodeBook, short frame_size, short vsize,
       short min_pitch, struct frame *bs, short *output, short smpnum)
{
    short    count;
    short    *bptr, *sptr1, *sptr2;
    unsigned short pitch, bcode;
/*
    short qlb_tab[] = {
        1, 2, 3, 4, 5, 6, 7, 8,
        9, 10, 11, 12, 13, 14, 15, 16
    };
*/
    bcode = bs->bcode;
    pitch = bs->pitch + min_pitch - 1;

    /* Decode VQ vectors */
    {
        unsigned    char    *cptr;
        short    k, vsize_by_2;
        short    rshift_count = 7 - bs->gcode; /* We want the output to be 14-bit
number */

        sptr1 = output + smpnum;
        cptr = bs->vqcode;
        vsize_by_2 = (vsize >> 1) + 1; /* + 1 since we do a while (--i) instead of
while (i--) */
        if (rshift_count)
        {
            for (k = 0; k < frame_size; k += vsize)
            {
                bptr = DecodeBook[*cptr++];
                count = vsize_by_2;
                while (--count)
                {
                    *sptr1++ = ((*bptr++) >> rshift_count);
                    *sptr1++ = ((*bptr++) >> rshift_count);
                }
            }
        }
    }
}

```

- 45 -

```

else
{
    for (k = 0; k < frame_size; k += vsize)
    {
        bptr = DecodeBook(*cptr++);
        count = vsize_by_2;
        while (--count)
        {
            *sptr1++ = *bptr++;
            *sptr1++ = *bptr++;
        }
    }
}

/* Inverse Filtering */
if (smpnum < pitch)
{
    sptr1 = output + pitch;
    count = smpnum + frame_size + 1 - pitch; /* +1 since we do a while (--i)
instead of while (i--) */
    sptr2 = sptr1 - pitch;
    switch (bcode)
    {
        case 0:
            while (--count)
                *sptr1++ += ((*sptr2++) >> 4);
            break;
        case 1:
            while (--count)
                *sptr1++ += ((*sptr2++) >> 3);
            break;
        case 2:
            while (--count)
                *sptr1++ += ((3 * (*sptr2++)) >> 4);
            break;
        case 3:
            while (--count)
                *sptr1++ += ((*sptr2++) >> 2);
            break;
        case 4:
            while (--count)
                *sptr1++ += ((5 * (*sptr2++)) >> 4);
            break;
        case 5:
            while (--count)
                *sptr1++ += ((3 * (*sptr2++)) >> 3);
            break;
        case 6:
            while (--count)

```

- 46 -

```
    *sptr1++ += ((7 * (*sptr2++)) >> 4);
break;
case 7:
    while (--count)
        *sptr1++ += ((*sptr2++) >> 1);
break;
case 8:
    while (--count)
    {
        long tmp;
        tmp = *sptr2++;
        *sptr1++ += (((tmp << 3) + tmp) >> 4);
    }
break;
case 9:
    while (--count)
        *sptr1++ += ((5 * (*sptr2++)) >> 3);
break;
case 10:
    while (--count)
    {
        long tmp;
        tmp = *sptr2++;
        *sptr1++ += (((tmp << 3) + 3 * tmp) >> 4);
    }
break;
case 11:
    while (--count)
        *sptr1++ += ((3 * (*sptr2++)) >> 2);
break;
case 12:
    while (--count)
    {
        long tmp;
        tmp = *sptr2++;
        *sptr1++ += (((tmp << 4) - 3 * tmp) >> 4);
    }
break;
case 13:
    while (--count)
        *sptr1++ += ((7 * (*sptr2++)) >> 3);
break;
case 14:
    while (--count)
    {
        long tmp;
        tmp = *sptr2++;
        *sptr1++ += (((tmp << 4) - tmp) >> 4);
    }
break;
```

- 47 -

```
case 15:
    while (--count)
        *sptr1++ += *sptr2++;
    break;
}
} else {
    sptr1 = output + smpnum;
    sptr2 = sptr1 - pitch;
    count = (frame_size / 4) + 1;
    switch (bcode)
    {
        case 0:
            while (--count) {
                *sptr1++ += ((*sptr2++) >> 4);
                *sptr1++ += ((*sptr2++) >> 4);
                *sptr1++ += ((*sptr2++) >> 4);
                *sptr1++ += ((*sptr2++) >> 4);
            }
            break;
        case 1:
            while (--count) {
                *sptr1++ += ((*sptr2++) >> 3);
                *sptr1++ += ((*sptr2++) >> 3);
                *sptr1++ += ((*sptr2++) >> 3);
                *sptr1++ += ((*sptr2++) >> 3);
            }
            break;
        case 2:
            while (--count) {
                *sptr1++ += ((3 * (*sptr2++)) >> 4);
                *sptr1++ += ((3 * (*sptr2++)) >> 4);
                *sptr1++ += ((3 * (*sptr2++)) >> 4);
                *sptr1++ += ((3 * (*sptr2++)) >> 4);
            }
            break;
        case 3:
            while (--count) {
                *sptr1++ += ((*sptr2++) >> 2);
                *sptr1++ += ((*sptr2++) >> 2);
                *sptr1++ += ((*sptr2++) >> 2);
                *sptr1++ += ((*sptr2++) >> 2);
            }
            break;
        case 4:
            while (--count) {
                *sptr1++ += ((5 * (*sptr2++)) >> 4);
                *sptr1++ += ((5 * (*sptr2++)) >> 4);
                *sptr1++ += ((5 * (*sptr2++)) >> 4);
                *sptr1++ += ((5 * (*sptr2++)) >> 4);
            }
    }
}
```

- 48 -

```

        break;
case 5:
    while (--count) {
        *sptr1++ += ((3 * (*sptr2++)) >> 3);
        *sptr1++ += ((3 * (*sptr2++)) >> 3);
        *sptr1++ += ((3 * (*sptr2++)) >> 3);
        *sptr1++ += ((3 * (*sptr2++)) >> 3);
    }
    break;
case 6:
    while (--count) {
        *sptr1++ += ((7 * (*sptr2++)) >> 4);
        *sptr1++ += ((7 * (*sptr2++)) >> 4);
        *sptr1++ += ((7 * (*sptr2++)) >> 4);
        *sptr1++ += ((7 * (*sptr2++)) >> 4);
    }
    break;
case 7:
    while (--count) {
        *sptr1++ += ((*sptr2++) >> 1);
        *sptr1++ += ((*sptr2++) >> 1);
        *sptr1++ += ((*sptr2++) >> 1);
        *sptr1++ += ((*sptr2++) >> 1);
    }
    break;
case 8:
    while (--count) {
        long tmp;
        tmp = *sptr2++;
        *sptr1++ += ((8 * tmp + tmp) >> 4);
        tmp = *sptr2++;
        *sptr1++ += ((8 * tmp + tmp) >> 4);
        tmp = *sptr2++;
        *sptr1++ += ((8 * tmp + tmp) >> 4);
        tmp = *sptr2++;
        *sptr1++ += ((8 * tmp + tmp) >> 4);
    }
    break;
case 9:
    while (--count) {
        *sptr1++ += ((5 * (*sptr2++)) >> 3);
        *sptr1++ += ((5 * (*sptr2++)) >> 3);
        *sptr1++ += ((5 * (*sptr2++)) >> 3);
        *sptr1++ += ((5 * (*sptr2++)) >> 3);
    }
    break;
case 10:
    while (--count) {
        long tmp;
        tmp = *sptr2++;

```

- 49 -

```

*sptr1++ += (((tmp << 3) + 3 * tmp) >> 4);
tmp = *sptr2++;
*sptr1++ += (((tmp << 3) + 3 * tmp) >> 4);
tmp = *sptr2++;
*sptr1++ += (((tmp << 3) + 3 * tmp) >> 4);
tmp = *sptr2++;
*sptr1++ += (((tmp << 3) + 3 * tmp) >> 4);
}
break;
case 11:
while (--count) {
    *sptr1++ += ((3 * (*sptr2++)) >> 2);
    *sptr1++ += ((3 * (*sptr2++)) >> 2);
    *sptr1++ += ((3 * (*sptr2++)) >> 2);
    *sptr1++ += ((3 * (*sptr2++)) >> 2);
}
break;
case 12:
while (--count) {
    long tmp;
    tmp = *sptr2++;
    *sptr1++ += (((tmp << 4) - 3 * tmp) >> 4);
    tmp = *sptr2++;
    *sptr1++ += (((tmp << 4) - 3 * tmp) >> 4);
    tmp = *sptr2++;
    *sptr1++ += (((tmp << 4) - 3 * tmp) >> 4);
    tmp = *sptr2++;
    *sptr1++ += (((tmp << 4) - 3 * tmp) >> 4);
}
break;
case 13:
while (--count) {
    *sptr1++ += ((7 * (*sptr2++)) >> 3);
    *sptr1++ += ((7 * (*sptr2++)) >> 3);
    *sptr1++ += ((7 * (*sptr2++)) >> 3);
    *sptr1++ += ((7 * (*sptr2++)) >> 3);
}
break;
case 14:
while (--count) {
    long tmp;
    tmp = *sptr2++;
    *sptr1++ += (((tmp << 4) - tmp) >> 4);
    tmp = *sptr2++;
    *sptr1++ += (((tmp << 4) - tmp) >> 4);
    tmp = *sptr2++;
    *sptr1++ += (((tmp << 4) - tmp) >> 4);
    tmp = *sptr2++;
    *sptr1++ += (((tmp << 4) - tmp) >> 4);
}
}

```

- 50 -

```

        break;
    case 15:
        while (--count) {
            *sptr1++ += *sptr2++;
            *sptr1++ += *sptr2++;
            *sptr1++ += *sptr2++;
            *sptr1++ += *sptr2++;
        }
        break;
    }
}

short SnDecompress(DecodeBook, ratio, frame_size, min_pitch, bstream, output)
short **DecodeBook, ratio;
unsigned char *bstream;
short *output, frame_size, min_pitch;
{
    short count, SampCount;
    register short dstate;
    short vcount;
    short vsize, cbook_size, bs_size;

    get_compr_pars(ratio, frame_size, &vsize, &cbook_size, &bs_size);

    dstate = *bstream++;
    dstate = (dstate - 128) << 6;

    SampCount = 0;
    while((*bstream & LAST_FRAME_FLAG) == 0)
    {
        expand(DecodeBook, frame_size, vsize, min_pitch,
               (struct frame *)bstream, output, SampCount);
        bstream += bs_size;
        SampCount += frame_size;
    }
    vcount = *bstream - LAST_FRAME_FLAG;
    *bstream = *(bstream + 2 + vcount);
    expand(DecodeBook, frame_size, vsize, min_pitch,
           (struct frame *)bstream, output, SampCount);
    *bstream = vcount + LAST_FRAME_FLAG;
    SampCount += vcount * vsize;

    count = (SampCount >> 1) + 1;
    while (--count) {
        *output++ = dstate = ((IPCONS * dstate) >> 3) + *output;
        *output++ = dstate = ((IPCONS * dstate) >> 3) + *output;
    }
    output -= SampCount;
}

```

- 51 -

```
    return SampCount;
}

#define FILTER state + PFILT_ORDER + 1
#define DC_VAL state + PFILT_ORDER + PFILT_ORDER/2 + 2
void SnSampExpandFilt(short *src, short off, short len,
    char *dest, short *state)
{
    short      input, temp;
    long       acc;
    register short dc = *(DC_VAL);
    register short *sptr1, *sptr2;

    src += off;
    len++;
    sptr1 = state;
    sptr2 = state + PFILT_ORDER;
    while (--len) {
        input = *src++ - dc;
        dc += input >> 5;

        temp = input + *sptr1++; /* (state[0] + state[8]) * filter[0] */
        acc = temp * *(FILTER);

        temp = *--sptr2 + *sptr1++; /* (state[1] + state[7]) * filter[1] */
        acc += temp * *(FILTER+1);

        temp = *--sptr2 + *sptr1++; /* (state[2] + state[6]) * filter[2] */
        acc += temp * *(FILTER+2);

        temp = *--sptr2 + *sptr1++; /* (state[3] + state[5]) * filter[3] */
        acc += temp * *(FILTER+3);

        acc += *sptr1 * *(FILTER+4); /* state[4] * filter[4] */

        if (acc > 0)
        {
            temp = (acc + (257 << 20)) >> 21;
            if (temp > 255)
                temp = 255;
        }
        else
        {
            temp = (acc + (255 << 20)) >> 21;
            if (temp < 0)
                temp = 0;
        }
        *dest++ = temp;
    }
}
```

- 52 -

```
    sptr1 -= 4;
    sptr2 -= 4;
    *sptr1++ = *sptr2++; /* state[0] = state[1] */
    *sptr1++ = *sptr2++; /* state[1] = state[2] */
    *sptr1++ = *sptr2++; /* state[2] = state[3] */
    *sptr1++ = *sptr2++; /* state[3] = state[4] */
    *sptr1++ = *sptr2++; /* state[4] = state[5] */
    *sptr1++ = *sptr2++; /* state[5] = state[6] */
    *sptr1++ = *sptr2++; /* state[6] = state[7] */
    *sptr1 = input;      /* state[7] = input */
    sptr1 -= 7;
}
*(DC_VAL) = dc;
}
```

- 53 -

III. BLENDING MODULE

```
/* A module for blending two diphones */

typedef struct {
    short lptr, pitch;
    short weight, weight_inc;
} bstate;

void SnBlend(pitchp lp, pitchp rp, short cur_tot, short tot,
             short type, bstate *bs)
{
    #pragma unused (tot)

    short count;
    short *ptr1, *ptr2;

    if (type == VOICED)
    {
        if (cur_tot)
            return;
        {
            short weight;
            long min_amdf;
            short best_lag = 0, lag;
            short window_size;
            short weight_inc;

            /* First replicate the left pitch period */
            ptr1 = lp->bufp;
            ptr2 = ptr1 + lp->olen;
            count = lp->olen + 1;
            while (--count)
                *ptr2++ = *ptr1++;

            /* Smooth the discontinuity */
            {
                register short en, e2;

                en = lp->bufp[2] +
                    3 * (lp->bufp[0] - lp->bufp[1]) - lp->bufp[lp->olen - 1];

                e2 = lp->bufp[0] - lp->bufp[lp->olen - 1];

                if (en * en > e2 * e2)
                    en = e2;
            }
        }
    }
}
```

- 54 -

```
ptr2 = lp->bufp + lp->olen;
count = (lp->olen >> 1) + 1;
while (--count)
{
    *--ptr2 += en;
    en = (((en << 4) - en) >> 4);
}
min_amdf = LARGE_NUM;

window_size = rp->olen;
if (lp->olen < rp->olen)
    window_size = lp->olen;

lag = rp->olen;
while (--lag)
{
    long amdf = 0;
    ptr1 = rp->bufp;
    ptr2 = lp->bufp + lag;
    count = ((window_size+3) >> 2) + 1;
    while (--count)
    {
        short tmp;
        tmp = (*ptr1 - *ptr2);
        if (tmp > 0)
            amdf += tmp;
        else
            amdf -= tmp;
        ptr1 += 4;
        ptr2 += 4;
    }
    if (amdf < min_amdf)
    {
        best_lag = lag;
        min_amdf = amdf;
    }
}

bs->pitch = lp->olen;
/* Update left buffer */
if (best_lag < (lp->olen >> 1))
{
    /* Add best_lag samples to the length of left pulse */
    lp->olen += best_lag;
}
else
{
    /* Delete a few samples from the left pulse */
}
```

- 55 -

```
    lp->olen = best_lag;
}
bs->lptr = best_lag;
weight_inc = 32767/window_size;
weight = 32767 - weight_inc;

ptr1 = rp->bufp;
ptr2 = lp->bufp + bs->lptr;
count = window_size + 1;
while (-count)
{
    *ptr1++ = (((short) (*ptr2++ - *ptr1) * weight) >> 15);
    weight -= weight_inc;
}
}
else
{
    register short delta;

    /* Just blend 15 samples */
    ptr2 = lp->bufp + lp->olen - 15;
    ptr1 = rp->bufp;
/*
    for (i = 1; i < 16; i++)
    {
        *ptr1 = *ptr2 + (i * (*ptr1 - *ptr2)) >> 4;
        ptr1++;
        ptr2++;
    }
*/
    delta = *ptr1 - *ptr2;
    *ptr1++ = *ptr2++ + (delta >> 4);

    delta = *ptr1 - *ptr2;
    *ptr1++ = *ptr2++ + ((delta) >> 3);

    delta = *ptr1 - *ptr2;
    *ptr1++ = *ptr2++ + ((3 * delta) >> 4);

    delta = *ptr1 - *ptr2;
    *ptr1++ = *ptr2++ + (delta >> 2);

    delta = *ptr1 - *ptr2;
    *ptr1++ = *ptr2++ + ((5 * delta) >> 4);

    delta = *ptr1 - *ptr2;
    *ptr1++ = *ptr2++ + ((3 * delta) >> 8);

    delta = *ptr1 - *ptr2;
```

- 56 -

```
*ptr1++ = *ptr2++ + ((7 * delta) >> 4);

delta = *ptr1 - *ptr2;
*ptr1++ = *ptr2++ + (delta >> 1);

delta = *ptr1 - *ptr2;
*ptr1++ = *ptr2++ + (((delta << 3) + delta) >> 4);

delta = *ptr1 - *ptr2;
*ptr1++ = *ptr2++ + ((5 * delta) >> 3);

delta = *ptr1 - *ptr2;
*ptr1++ = *ptr2++ + (((delta << 3) + 3 * delta) >> 4);

delta = *ptr1 - *ptr2;
*ptr1++ = *ptr2++ + ((3 * delta) >> 2);

delta = *ptr1 - *ptr2;
*ptr1++ = *ptr2++ + (((delta << 4) - 3 * delta) >> 4);

delta = *ptr1 - *ptr2;
*ptr1++ = *ptr2++ + ((7 * delta) >> 3);

delta = *ptr1 - *ptr2;
*ptr1 = *ptr2 + (((delta << 4) - delta) >> 4);

lp->olen -= 15;
}
```

- 57 -

IV. INTONATION ADJUSTMENT MODULE

```
/* A module for deleting a pitch period */
/*
Pointer src1 points to Left Pitch period
Pointer src2 points to Right Pitch period
Pointer dst points to Resulting Pitch period
len = length of the pitch periods
*/
skip_pulses(short *src1, short *src2, short *dst, short len)
{
    short i;
    register short    weight, cweight;

    i = len + 1;
    weight = cweight = 32767/i;
    while (--i)
    {
        *dst++ = *src1++ + (((short) (*src2++ - *src1) * cweight) >> 15);
        cweight += weight;
    }
}

/* A module for Inserting a pitch period */
/*
Locn buffer[curbeg] points to Left Pitch period
Locn buffer[curbeg+curlen] points to Right Pitch period
Pointer dst points to Resulting Pitch period
curlen = length of the pitch periods
*/
insert_pulse(short *buffer, short *dst, short curlen, short curbeg)
{
    short    weight, cweight, count;
    short    *src1, *src2;

    src1 = buffer + curbeg;
    src2 = buffer + curbeg + curlen;
    weight = 32767 / curlen;
    cweight = weight;
    count = curlen + 1;
    while (--count)
    {
        *dst++ = *src1++ = *src2++ + (((short) (*src1 - *src2) * cweight) >>
15);
        cweight += weight;
    }
}

/* This module is used to change pitch information in the concatenated speech */
```

- 58 -

// This routine depends on the desired length (deslen) being at least half
// and no more than twice the actual length (len).

```
void SnChangePitch(short *buf, short *next, short len, short deslen, short lvoc, short
rvoc, short dosmooth)
{
    #pragma unused(rvoc, dosmooth)
    short    delta;
    short    count;
    short    *bptr, *aptr;
    short    weight, weight_inc;
    if (!lvoc || (deslen == len)) return;

    if (deslen > len)
    {
        /* Increase Pitch period */
        delta = deslen - len;
        bptr = buf + len;
        aptr = buf + deslen;
        count = delta + 1;
        while (--count)
            *--aptr = *--bptr;

        count = len - delta + 1;
        weight = weight_inc = 32767 / count;
        while (--count)
        {
            register short tmp2;
            tmp2 = (*--aptr - *--bptr);
            *aptr = *bptr + ((tmp2 * weight) >> 15);
            weight += weight_inc;
        }
        return;
    }
    /* Shorten Pitch Period */
    short wsize;

    delta = len - deslen;
    wsize = 2 * delta;

    if (wsize > deslen)
        wsize = deslen;

    weight_inc = 32767 / (wsize + 1);
    weight = weight_inc;
    aptr = buf + deslen;
    bptr = buf + len - wsize;
    count = wsize - delta + 1;
```

- 59 -

```
while (--count)
{
    *bptr++ += (((short) (*aptr++ - *bptr) * weight) >> 15);
    weight += weight_inc;
}
aptr = buf + deslen;
bptr = next;
count = delta + 1;
weight = 32767 - weight;
while (--count)
{
    *bptr++ += (((short) (*aptr++ - *bptr) * weight) >> 15);
    weight -= weight_inc;
}
}
```

- 60 -

CLAIMS

What is claimed is:

1 1. An apparatus for concatenating a first digital frame of N
2 samples having respective magnitudes representing a first quasi-
3 periodic waveform and a second digital frame of M samples having
4 respective magnitudes representing a second quasi-periodic
5 waveform, comprising:

6 a buffer store to store the samples of first and second digital
7 frames;

8 means, coupled to the buffer store, for determining a blend point
9 for the first and second digital frames in response to magnitudes of
10 samples in the first and second digital frames;

11 blending means, coupled with the buffer store and the means for
12 determining, for computing a digital sequence representing a
13 concatenation of the first and second quasi-periodic waveforms in
14 response to the first frame, the second frame and the blend point.

1 2. The apparatus of claim 1, further including:

2 transducer means, coupled to the means for computing, for
3 transducing the digital sequence to an analog concatenated
4 waveform.

1 3. The apparatus of claim 1, wherein the means for
2 determining includes:

3 first means for computing an extended frame in response to the
4 first digital frame;

5 second means for finding a subset of the extended frame which
6 matches the second digital frame relatively well, and defining the
7 blend point as a sample in the subset.

1 4. The apparatus of claim 3, wherein the extended frame
2 comprises a concatenation of the first digital frame with a replica of
3 the first digital frame.

1 5. The apparatus of claim 3, wherein the subset of the
2 extended frame which matches the second digital frame relatively
3 well comprises a subset with a minimum average magnitude
4 difference over the samples in the subset, and the blend point
5 comprises a first sample in the subset.

1 6. The apparatus of claim 1, wherein the means for
2 determining includes:

3 first means for computing an extended frame comprising a
4 discontinuity-smoothed concatenation of the first digital frame with a
5 replica of the first digital frame;

6 second means for finding a subset of the extended frame with a
7 minimum average magnitude difference between the samples in the
8 subset and the second digital frame, and defining the blend point as a
9 first sample in the subset.

1 7. The apparatus of claim 1, wherein the blending means
2 includes:

- 62 -

3 means for supplying a first set of samples derived from the first
4 digital frame and the blend point as a first segment of the digital
5 sequence; and

6 means for combining the second digital frame with a second set
7 of samples derived from the first digital frame and the blend point,
8 with emphasis on the second set in a starting sample and emphasis
9 on the second digital frame in an ending sample to produce a second
10 segment of the digital sequence.

1 8. The apparatus of claim 1, wherein the means for
2 determining includes:

3 first means for computing an extended frame
4 comprising a discontinuity-smoothed concatenation of the
5 first digital frame with a replica of the first digital frame;

6 second means for finding a subset of the extended
7 frame with a minimum average magnitude difference
8 between the samples in the subset and the second digital
9 frame, and defining the blend point as a first sample in the
10 subset; and

11 wherein the blending means includes:

12 means for supplying a first set of samples derived
13 from the first digital frame and the blend point as a first
14 segment of the digital sequence; and

15 means for combining the second digital frame with
16 the subset of the extended frame, with emphasis on the
17 subset of the extended frame in a starting sample and
18 emphasis on the second digital frame in an ending sample
19 to produce a second segment of the digital sequence.

1 9. The apparatus of claim 8, wherein the first and second
2 digital frames represent endings and beginnings respectively of
3 adjacent diphones in speech, and further including:
4 transducer means, coupled to the blending means, for
5 transducing the digital sequence to an sound in speech synthesis.

1 10. An apparatus for concatenating a first digital frame of N
2 samples having respective magnitudes representing a first sound
3 segment and a second digital frame of M samples having respective
4 magnitudes representing a second sound segment, comprising:
5 a buffer store to store the samples of first and second digital
6 frames;
7 means, coupled to the buffer store, for determining a blend point
8 for the first and second digital frames in response to magnitudes of
9 samples in the first and second digital frames;
10 blending means, coupled with the buffer store and the means for
11 determining, for computing a digital sequence representing a
12 concatenation of the first and second quasi-periodic waveforms in
13 response to the first frame, the second frame and the blend point;
14 and
15 transducer means, coupled to the blending means, for
16 transducing the digital sequence to sound.

1 11. The apparatus of claim 10, wherein the means for
2 determining includes:
3 first means for computing an extended frame in response to the
4 first digital frame;
5 second means for finding a subset of the extended frame which
6 matches the second digital frame relatively well, and defining the
7 blend point as a sample in the subset.

- 64 -

1 12. The apparatus of claim 11, wherein the extended frame
2 comprises a concatenation of the first digital frame with a replica of
3 the first digital frame.

1 13. The apparatus of claim 11, wherein the subset of the
2 extended frame which matches the second digital frame relatively
3 well comprises a subset with a minimum average magnitude
4 difference over the samples in the subset, and the blend point
5 comprises a first sample in the subset.

1 14. The apparatus of claim 10, wherein the means for
2 determining includes:

3 first means for computing an extended frame comprising a
4 discontinuity-smoothed concatenation of the first digital frame with a
5 replica of the first digital frame;

6 second means for finding a subset of the extended frame with a
7 minimum average magnitude difference between the samples in the
8 subset and the second digital frame, and defining the blend point as a
9 first sample in the subset.

1 15. The apparatus of claim 10, wherein the blending means
2 includes:

3 means for supplying a first set of samples derived from the first
4 digital frame and the blend point as a first segment of the digital
5 sequence; and

6 means for combining the second digital frame with a second set
7 of samples derived from the first digital frame and the blend point,
8 with emphasis on the second set in a starting sample and emphasis
9 on the second digital frame in an ending sample to produce a second
10 segment of the digital sequence.

- 65 -

1 16. The apparatus of claim 10, wherein the means for
2 determining includes:

3 first means for computing an extended frame
4 comprising a discontinuity-smoothed concatenation of the
5 first digital frame with a replica of the first digital frame;
6 second means for finding a subset of the extended
7 frame with a minimum average magnitude difference
8 between the samples in the subset and the second digital
9 frame, and defining the blend point as a first sample in the
10 subset; and

11 wherein the blending means includes:

12 means for supplying a first set of samples derived
13 from the first digital frame and the blend point as a first
14 segment of the digital sequence; and

15 means for combining the second digital frame with
16 the subset of the extended frame, with emphasis on the
17 subset of the extended frame in a starting sample and
18 emphasis on the second digital frame in an ending sample
19 to produce a second segment of the digital sequence.

1 17. The apparatus of claim 16, wherein the first and second
2 digital frames represent endings and beginnings respectively of
3 adjacent diphones in speech, and the transducer means produces
4 synthesized speech.

1 18. An apparatus for synthesizing speech in response to a
2 text, comprising:
3 means for translating text to a sequence of sound segment
4 codes;
5 means, responsive to sound segment codes in the sequence, for
6 decoding the sequence of sound segment codes to produce strings of
7 digital frames of a plurality of samples representing sounds for
8 respective sound segment codes in the sequence, wherein the
9 identified strings of digital frames have beginnings and endings;
10 means for concatenating a first digital frame at the ending of an
11 identified string of digital frames of a particular sound segment code
12 in the sequence with a second digital frame at the beginning an
13 identified string of digital frames of an adjacent sound segment code
14 in the sequence to produce a speech data sequence, including
15 a buffer store to store the samples of first and
16 second digital frames;
17 means, coupled to the buffer store, for determining a
18 blend point for the first and second digital frames in
19 response to magnitudes of samples in the first and second
20 digital frames; and
21 blending means, coupled with the buffer store and
22 the means for determining, for computing a digital
23 sequence representing a concatenation of the first and
24 second sound segments in response to the first frame, the
25 second frame and the blend point; and
26 an audio transducer, coupled to the means for concatenating, to
27 generate synthesized speech in response to the speech data
28 sequence.

1 19. The apparatus of claim 18, further including:

- 67 -

2 means, responsive to the sound segment codes for adjusting
3 pitch and duration of the identified strings of digital frames in the
4 speech data sequence.

1 20. The apparatus of claim 18, wherein the means for
2 determining includes:

3 first means for computing an extended frame in response to the
4 first digital frame;

5 second means for finding a subset of the extended frame which
6 matches the second digital frame relatively well, and defining the
7 blend point as a sample in the subset.

1 21. The apparatus of claim 20, wherein the extended frame
2 comprises a concatenation of the first digital frame with a replica of
3 the first digital frame.

1 22. The apparatus of claim 20, wherein the subset of the
2 extended frame which matches the second digital frame relatively
3 well comprises a subset with a minimum average magnitude
4 difference over the samples in the subset, and the blend point
5 comprises a first sample in the subset.

1 23. The apparatus of claim 18, wherein the means for
2 determining includes:

3 first means for computing an extended frame comprising a
4 discontinuity-smoothed concatenation of the first digital frame with a
5 replica of the first digital frame;

6 second means for finding a subset of the extended frame with a
7 minimum average magnitude difference between the samples in the
8 subset and the second digital frame, and defining the blend point as a
9 first sample in the subset.

1 24. The apparatus of claim 18, wherein the blending means
2 includes:

3 means for supplying a first set of samples derived from the first
4 digital frame and the blend point as a first segment of the digital
5 sequence; and

6 means for combining the second digital frame with a second set
7 of samples derived from the first digital frame and the blend point,
8 with emphasis on the second set in a starting sample and emphasis
9 on the second digital frame in an ending sample to produce a second
10 segment of the digital sequence.

1 25. The apparatus of claim 18, wherein the means for
2 determining includes:

3 first means for computing an extended frame
4 comprising a discontinuity-smoothed concatenation of the
5 first digital frame with a replica of the first digital frame;
6 second means for finding a subset of the extended
7 frame with a minimum average magnitude difference
8 between the samples in the subset and the second digital
9 frame, and defining the blend point as a first sample in the
10 subset; and

11 wherein the blending means includes:

12 means for supplying a first set of samples derived
13 from the first digital frame and the blend point as a first
14 segment of the digital sequence; and

15 means for combining the second digital frame with
16 the subset of the extended frame, with emphasis on the
17 subset of the extended frame in a starting sample and
18 emphasis on the second digital frame in an ending sample
19 to produce a second segment of the digital sequence.

1 26. The apparatus of claim 18, wherein the sound segment
2 codes represent speech diphones, and the first and second digital
3 frames represent endings and beginnings respectively of adjacent
4 diphones in speech.

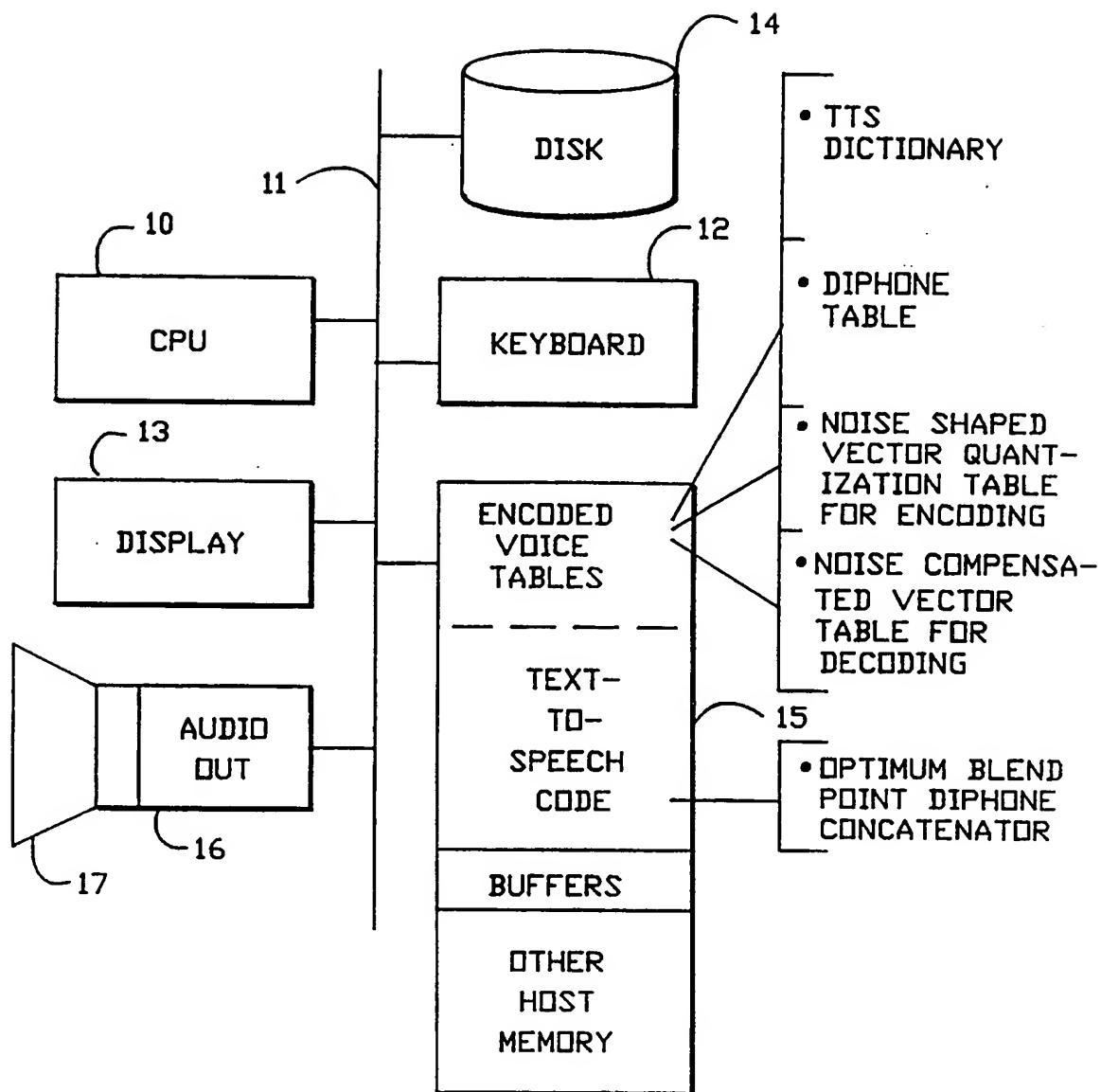
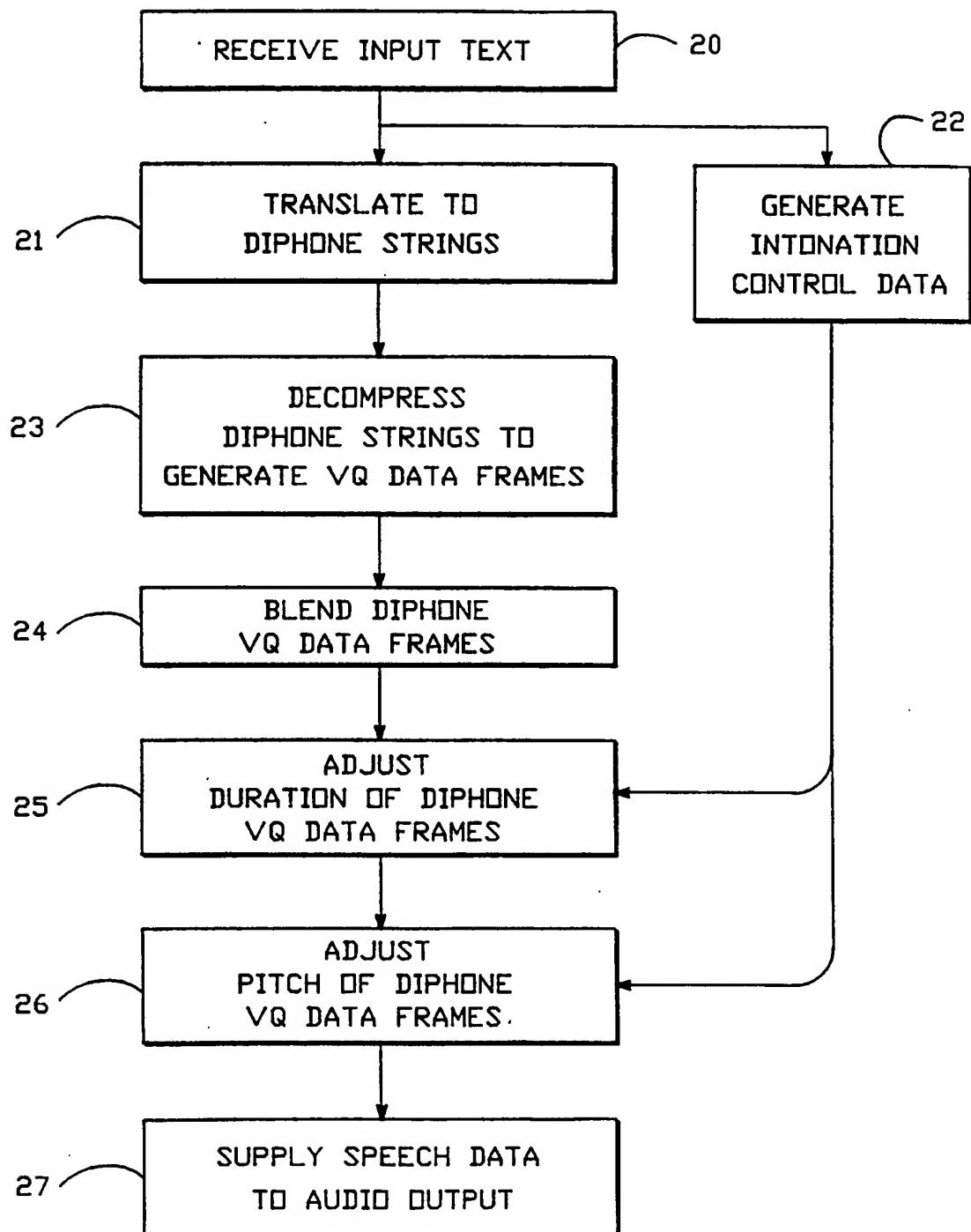


FIG. - 1



TEXT - TO - SPEECH CODE

FIG.-2

SUBSTITUTE SHEET

Diphone Record

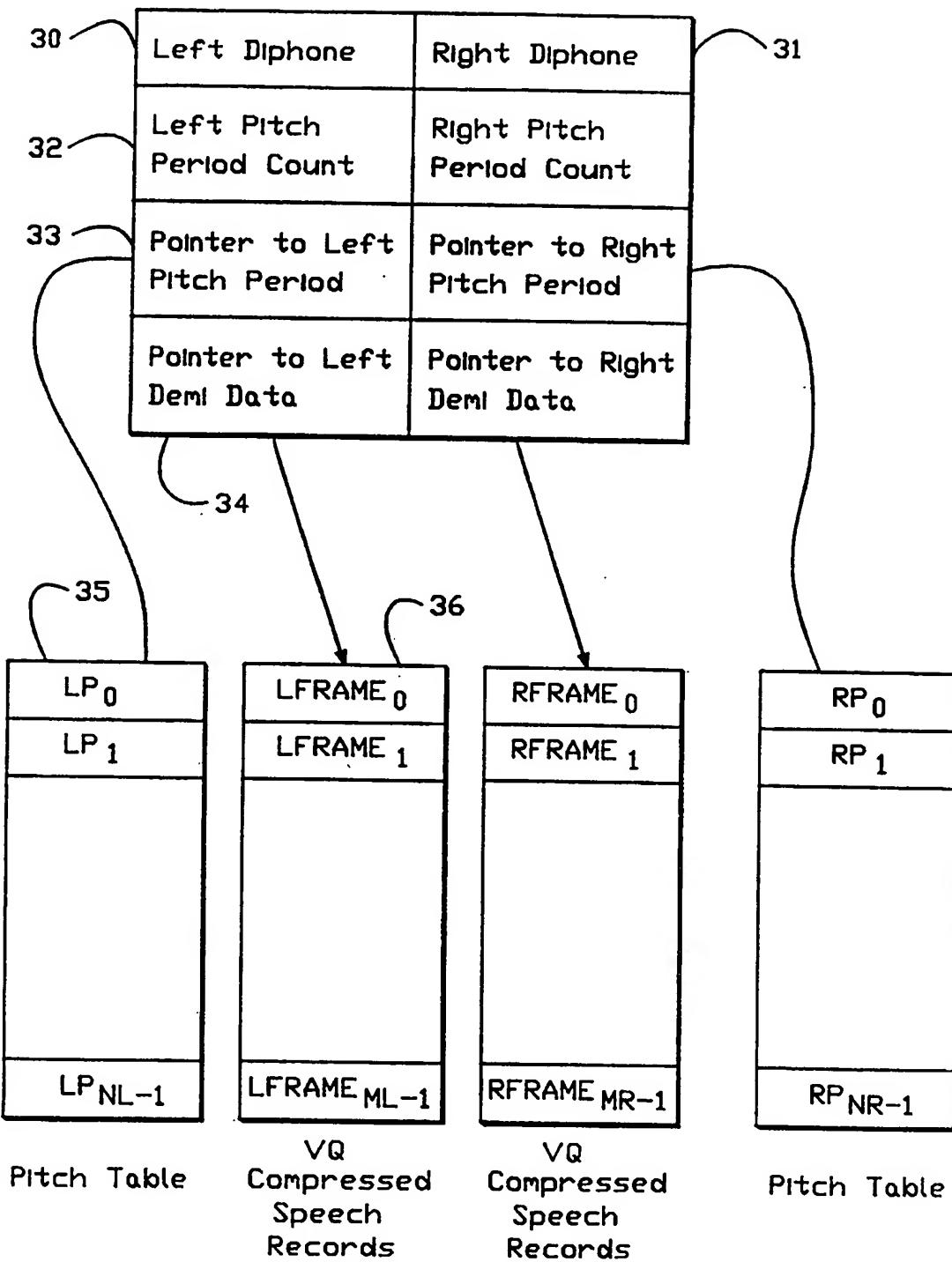


FIG.-3

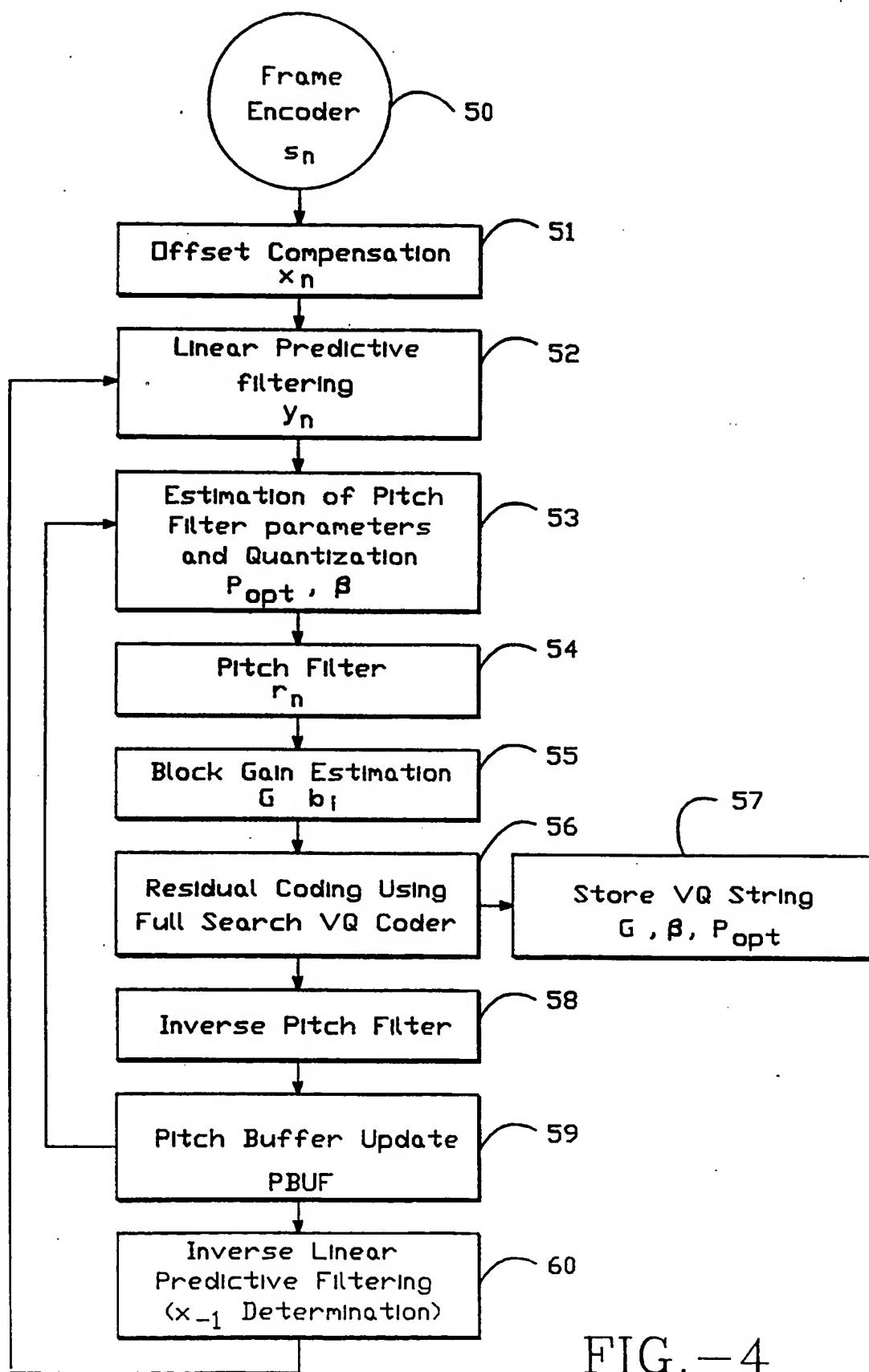


FIG. -4

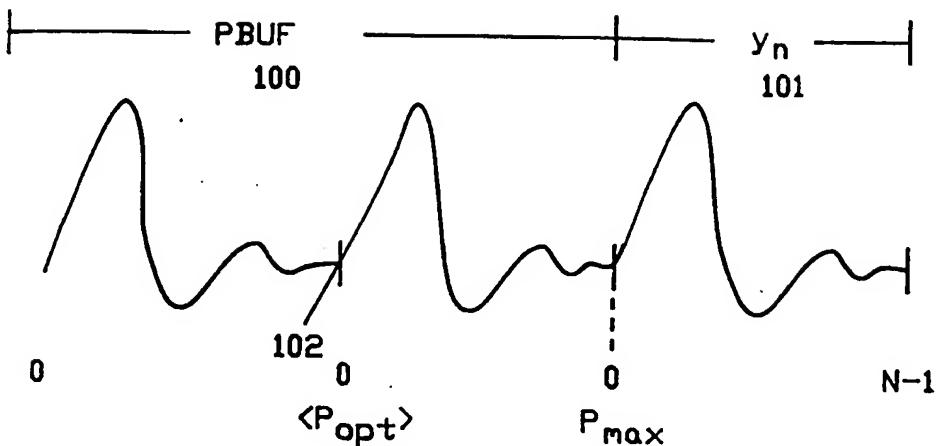


FIG.-5

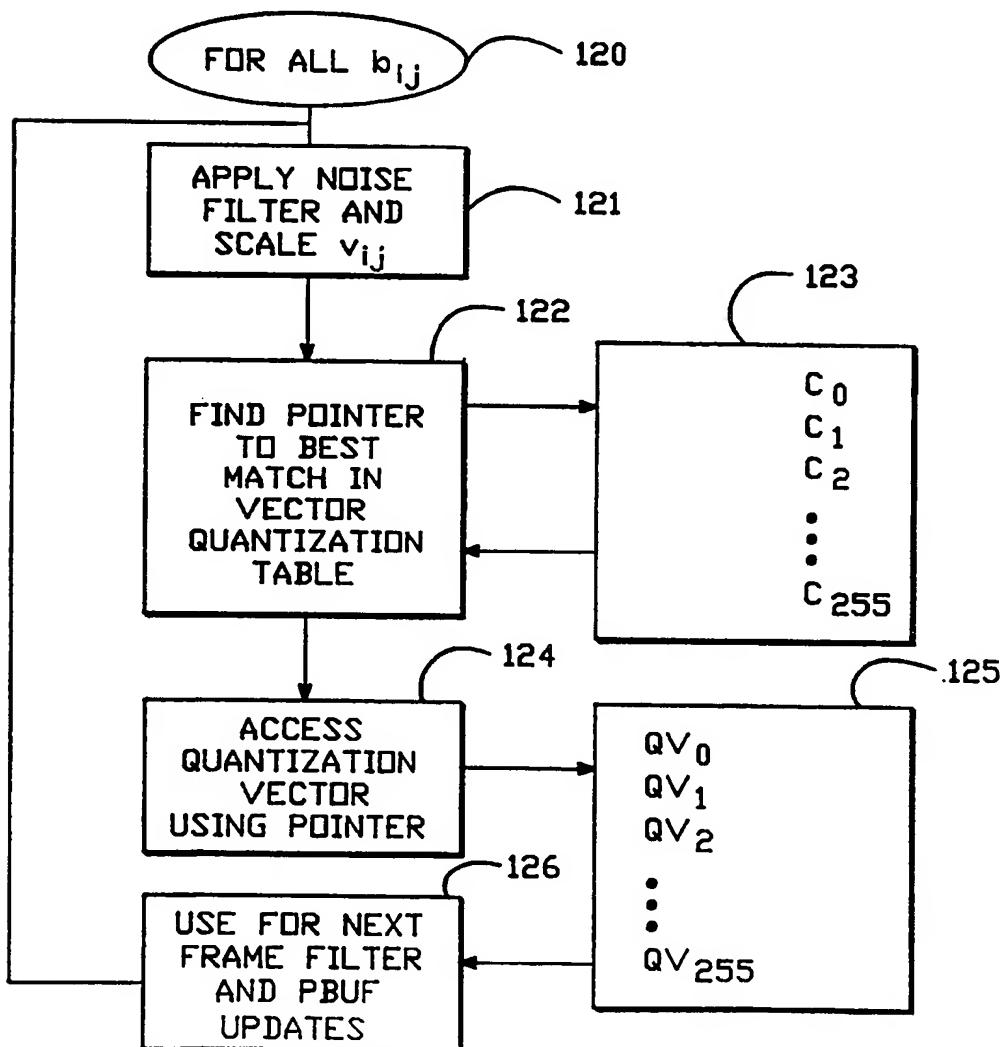


FIG.-6

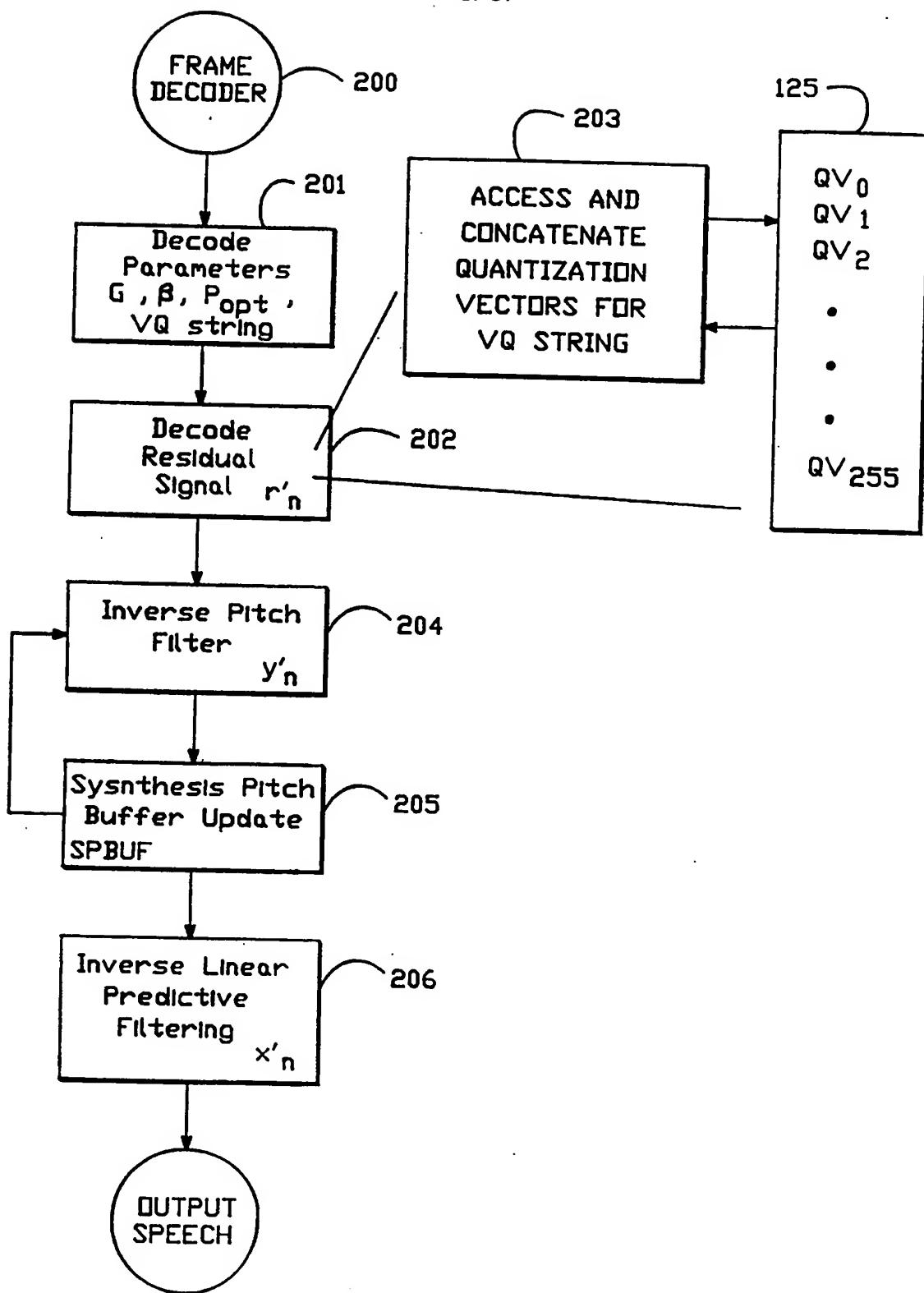


FIG.-7

7/17

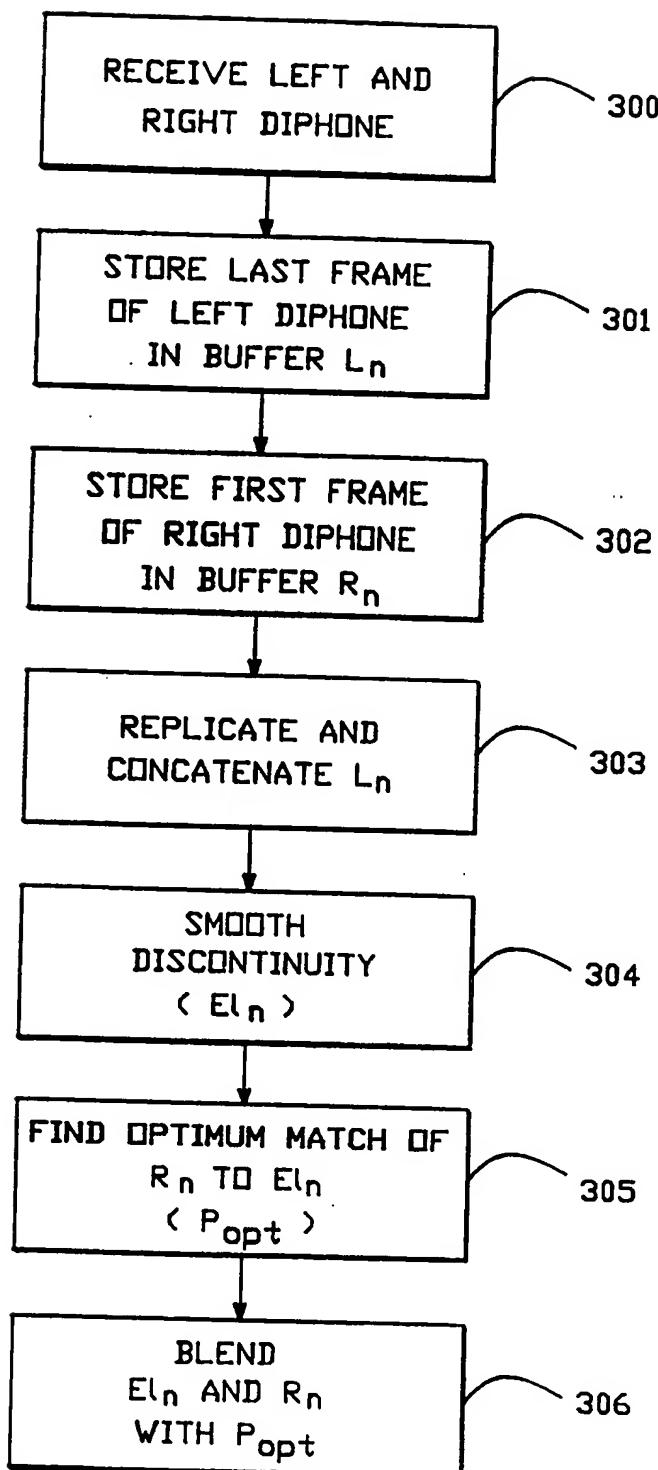


FIG.-8

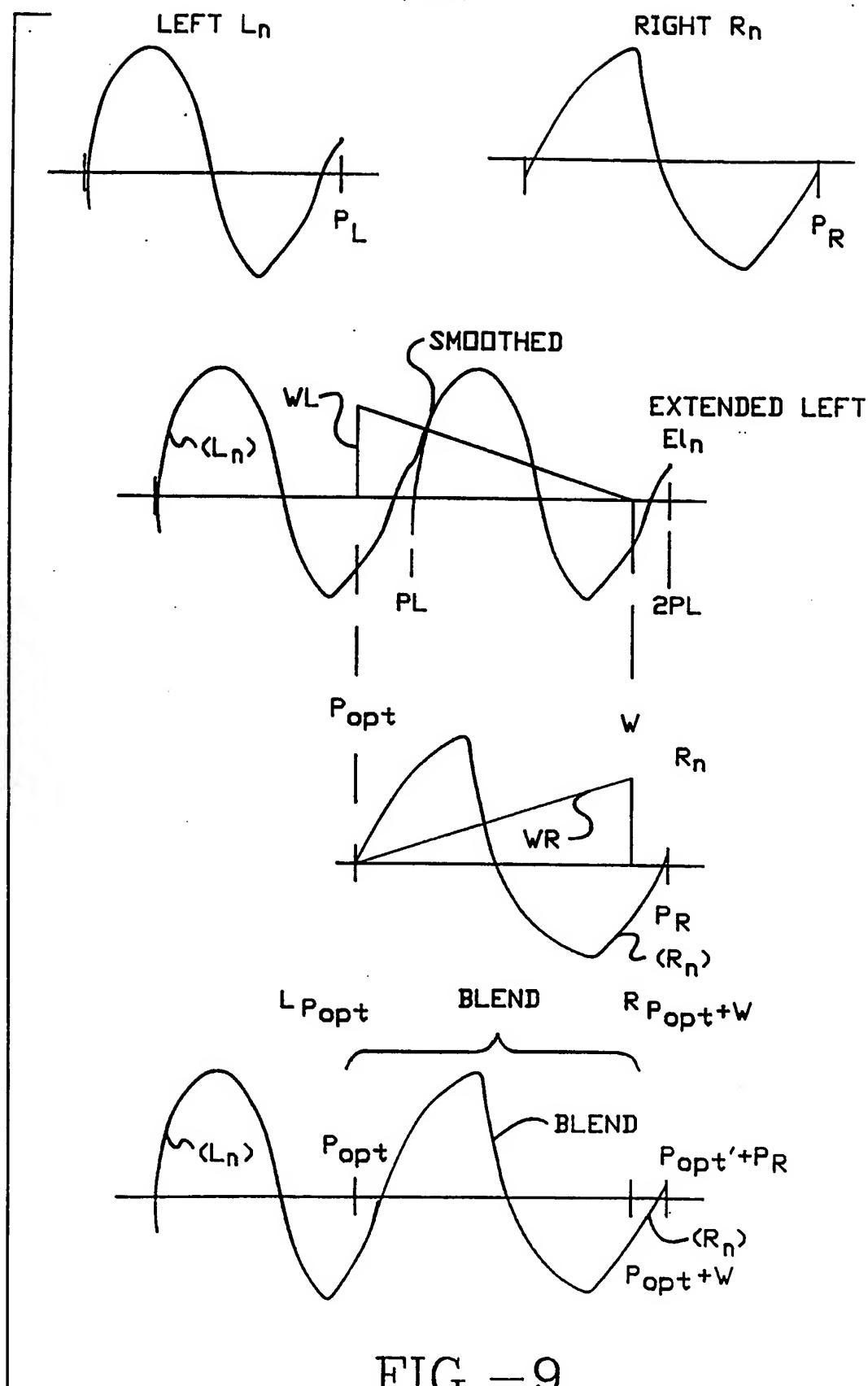
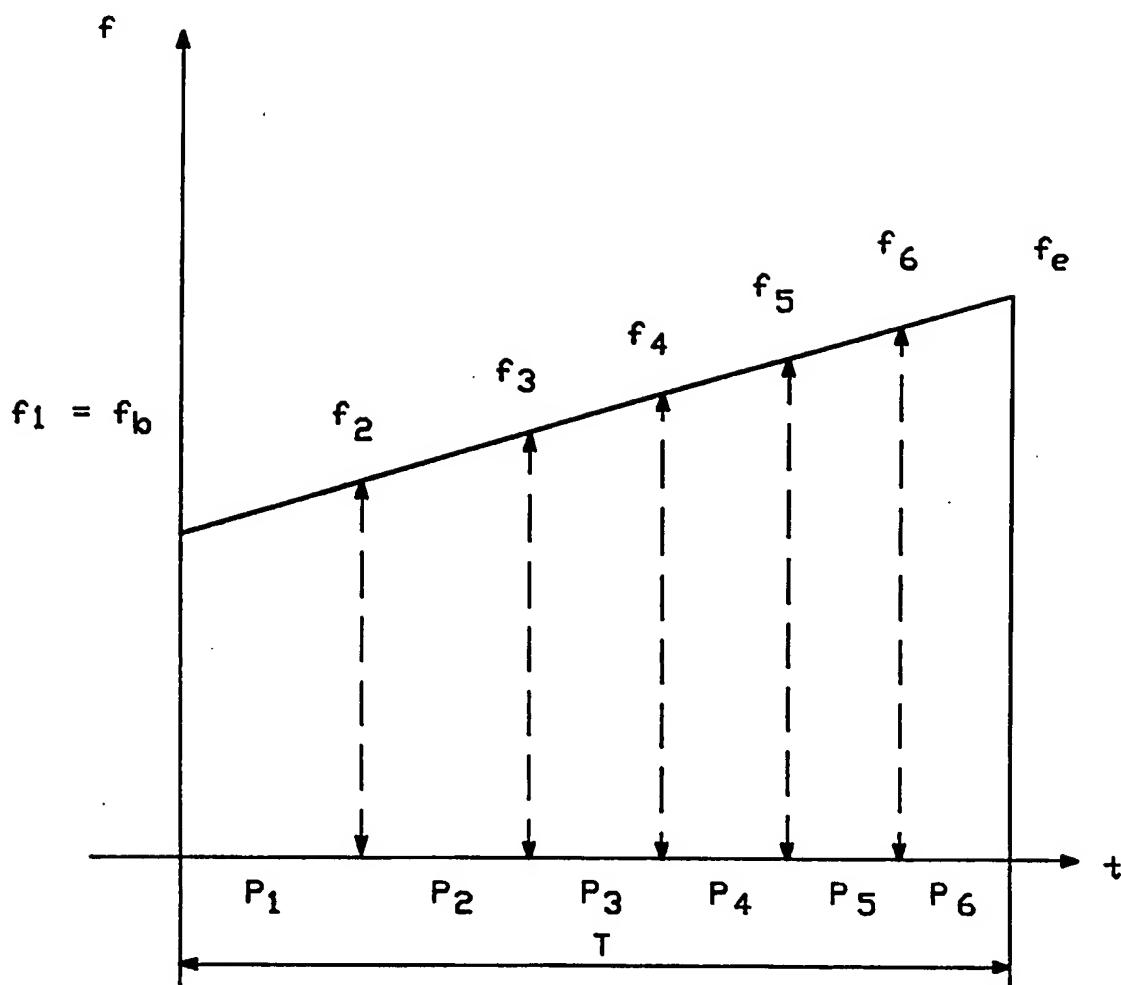


FIG. - 9



NOTES:

T = Desired duration of a phoneme

f_b = Desired Beginning Pitch in Hz

f_e = Desired Ending Pitch in Hz

P_1, P_2, \dots, P_6 are the desired pitch period in
No. of Samples corresponding to the frequencies
 f_1, f_2, \dots, f_6 .

Relationship between P_1 and f_1 :

$P_1 = F_s/f_1$, where F_s is the Sampling frequency.

FIG.-10

SUBSTITUTE SHEET

10/17

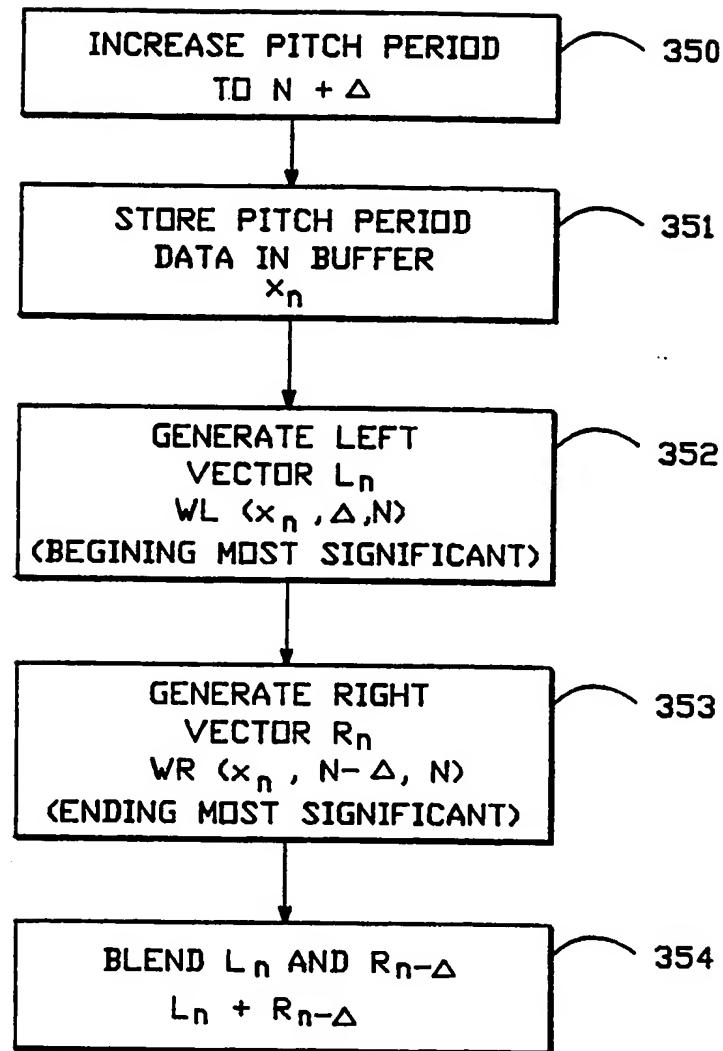


FIG.-11

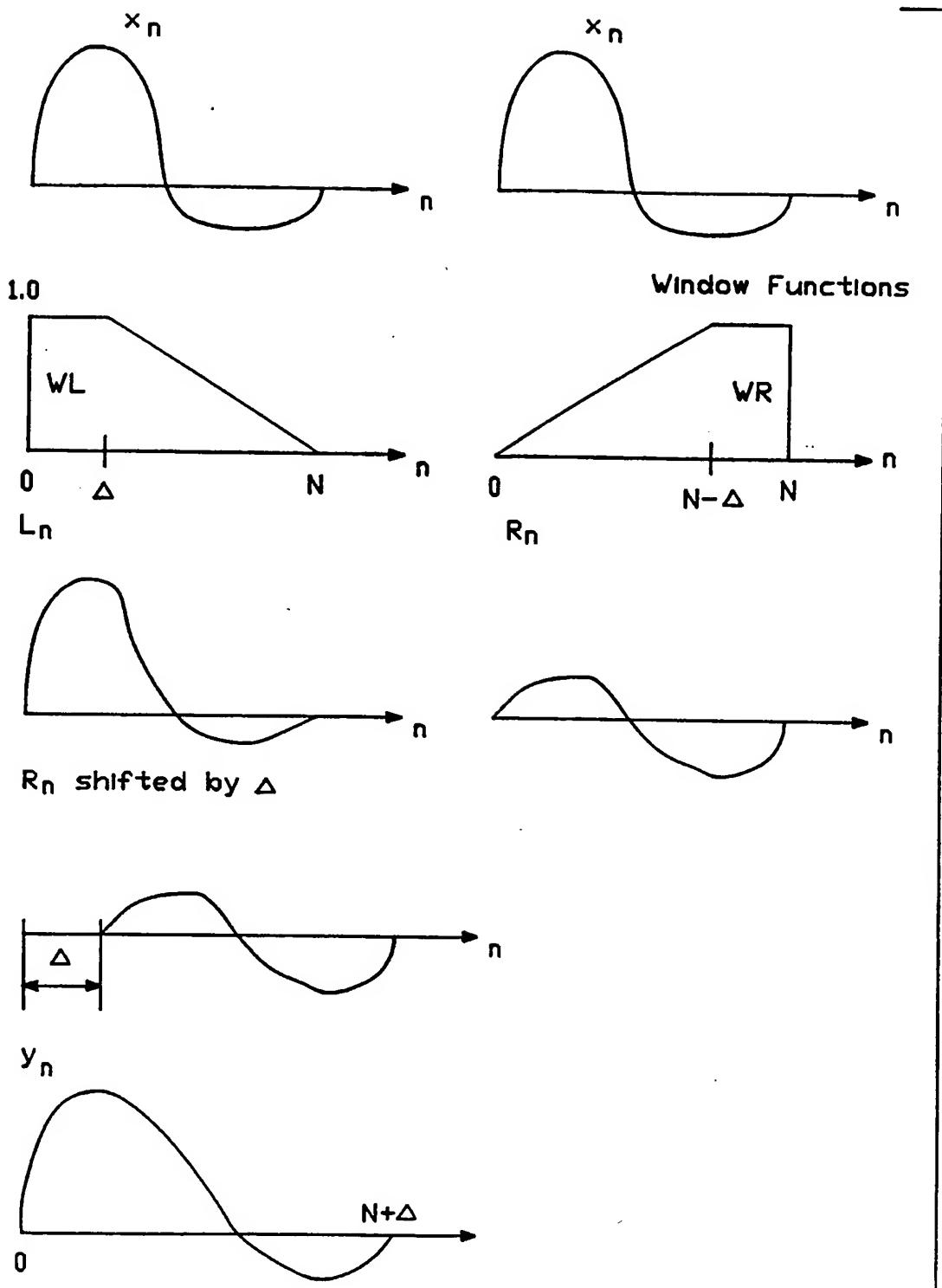


FIG.-12

12/17

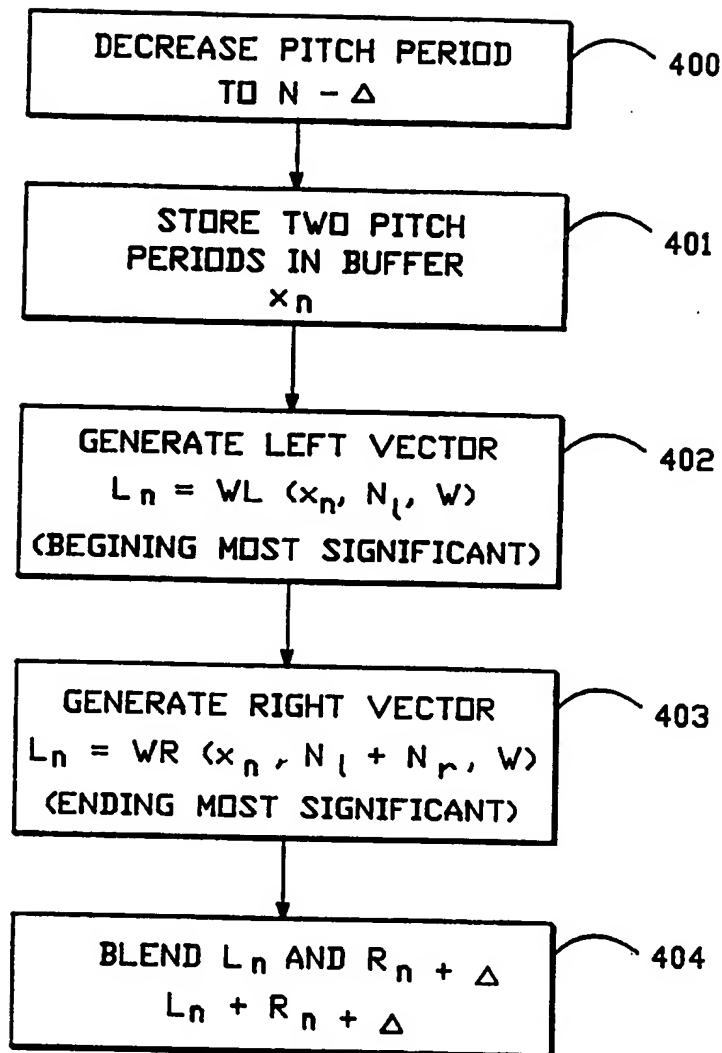


FIG.-13

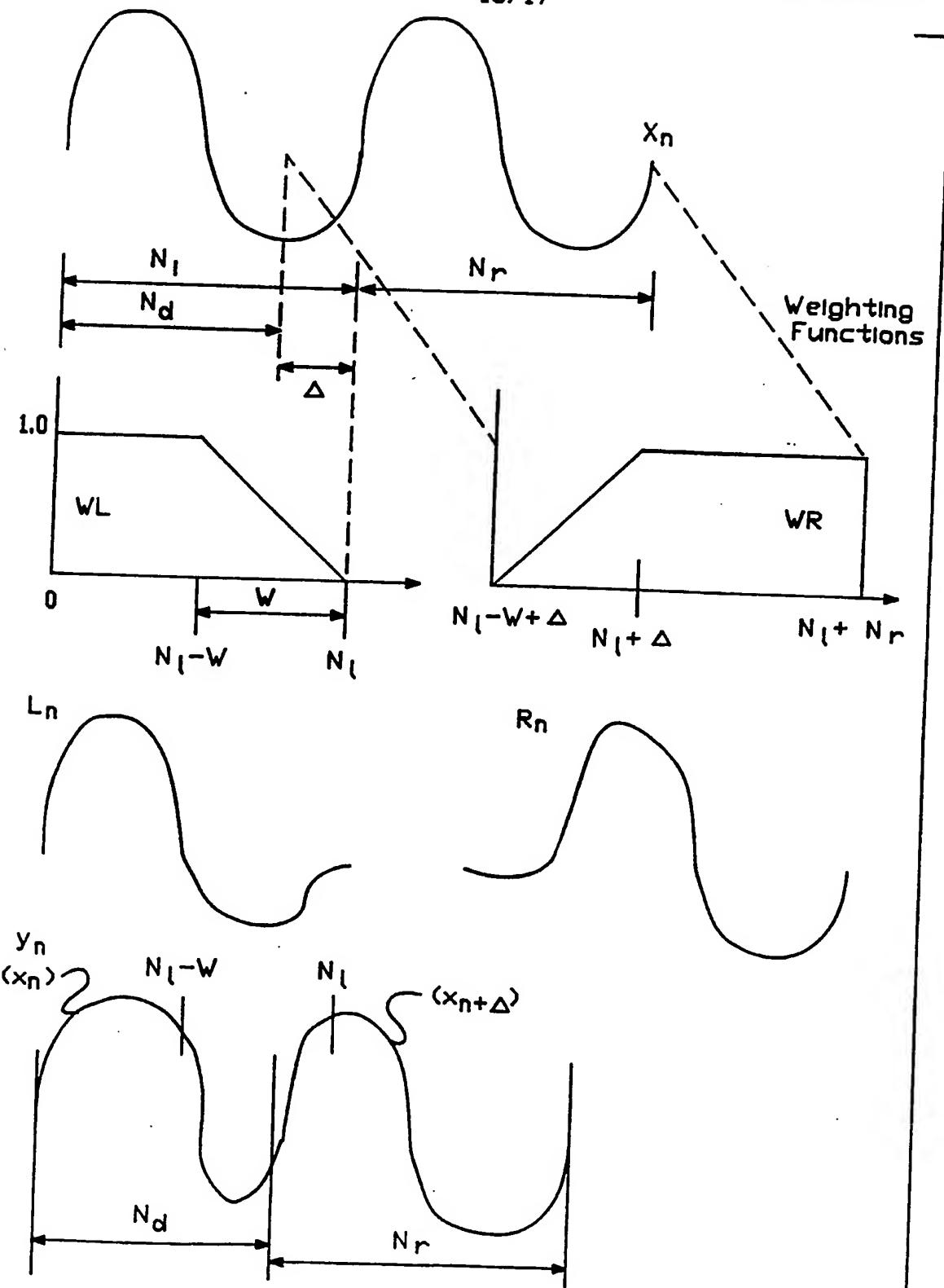


FIG.-14
SUBSTITUTE SHEET

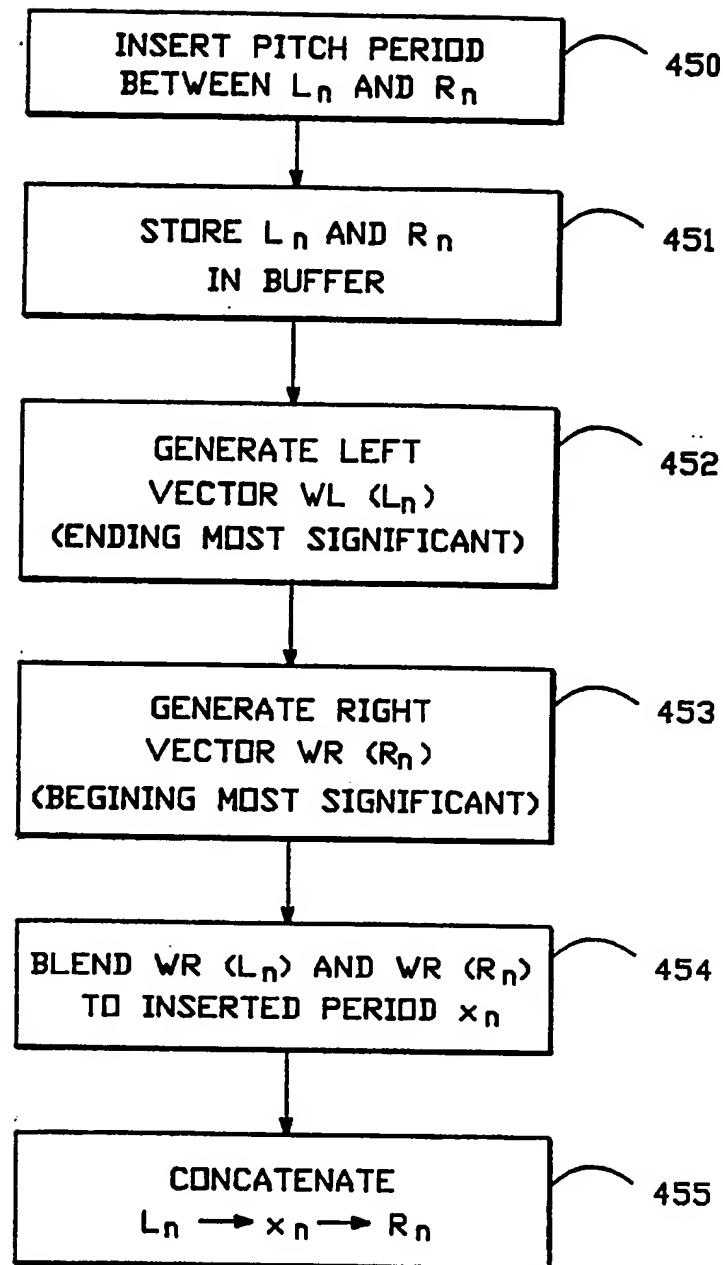


FIG.-15

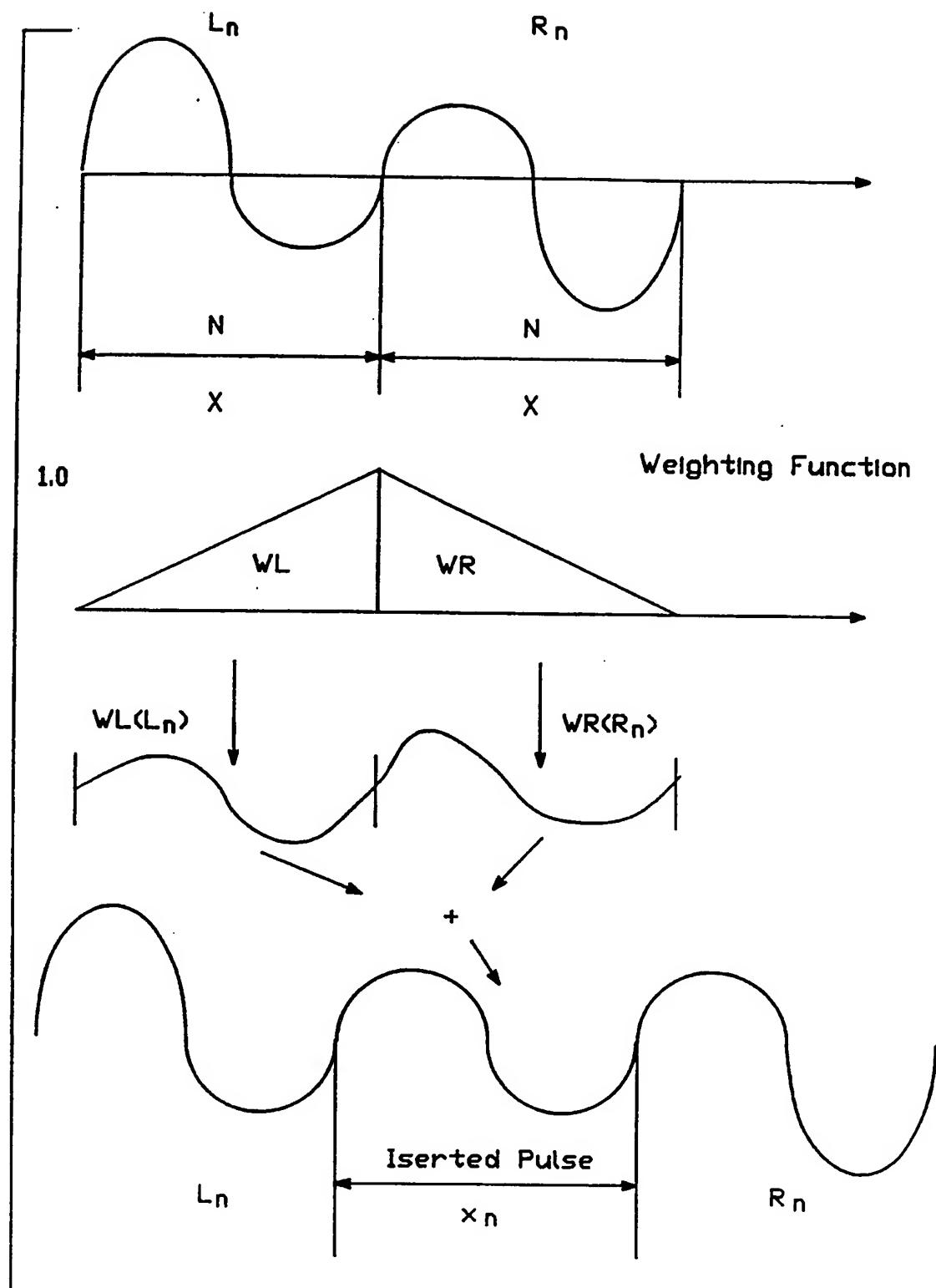


FIG.-16

SUBSTITUTE SHEET

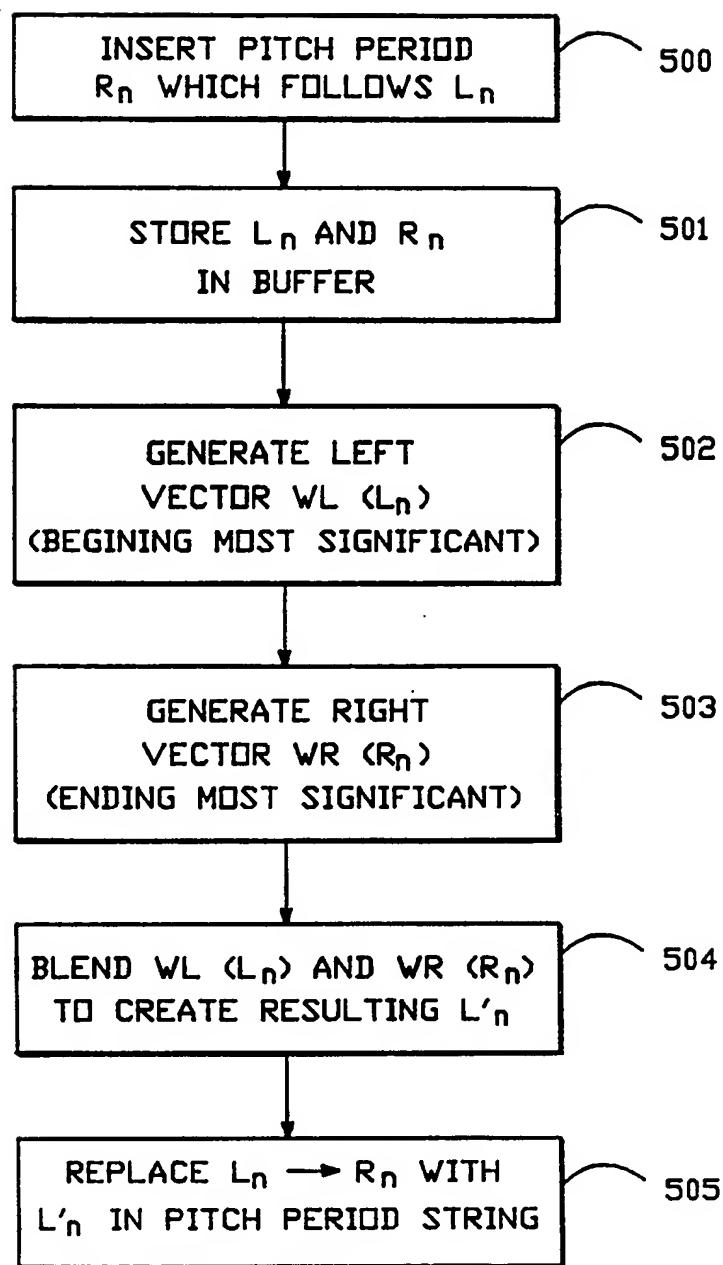


FIG.-17

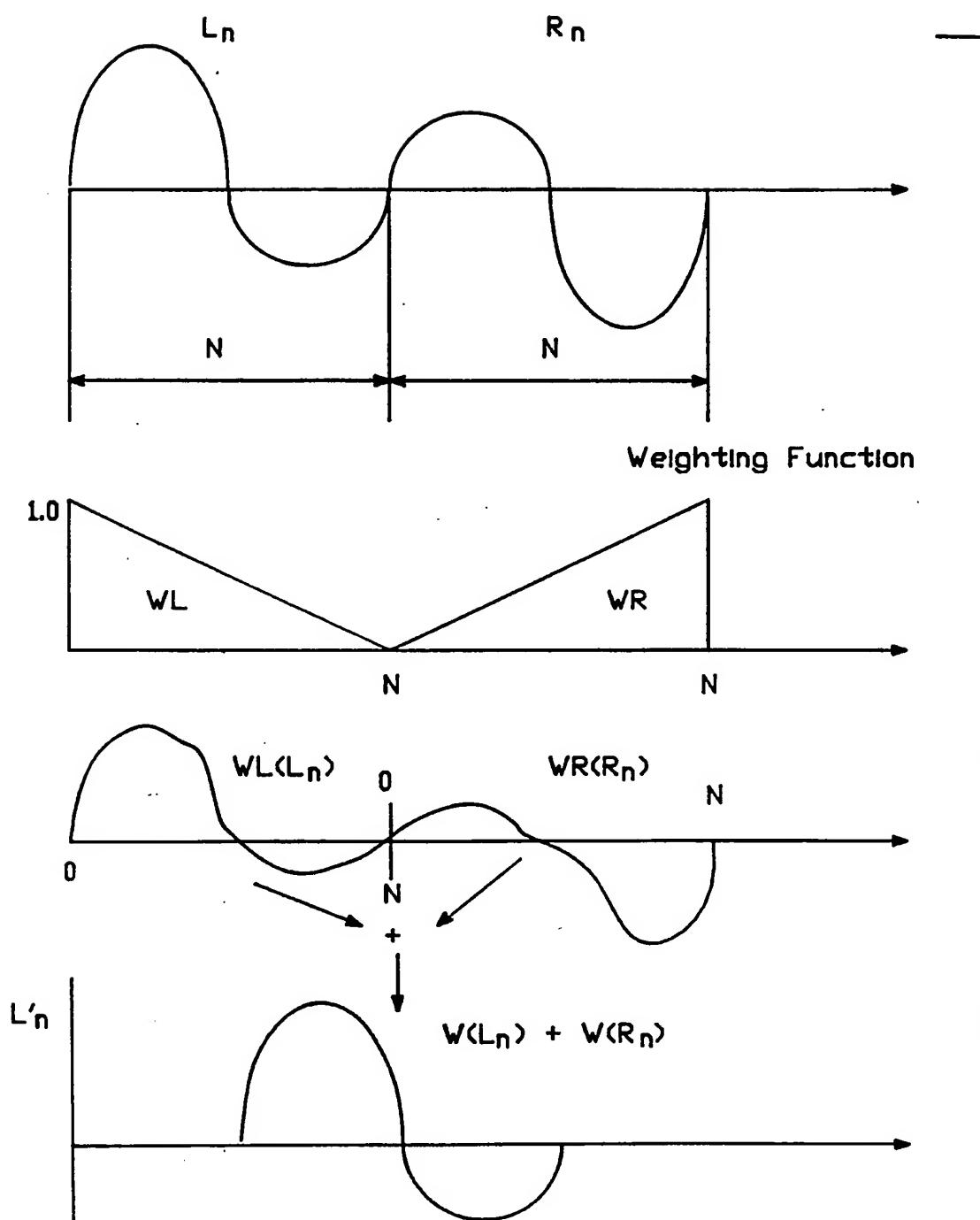


FIG.-18

INTERNATIONAL SEARCH REPORT

International Application No
PCT/US 94/00770

A. CLASSIFICATION OF SUBJECT MATTER

G 10 L 3/00, G 10 L 5/02, G 10 L 7/02, G 10 L 9/14

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

G 10 L 3/00, G 10 L 5/00, G 10 L 7/00, G 10 L 9/00

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	EP, A1, 0 515 709 (IBM) 02 December 1992 (02.12.92), fig. 1; abstract; claims 1,6,7. --	1,10, 18
A	EP, A1, 0 232 456 (AMERICAN TELEPHONE AND TELEGRAPH COMP.) 19 August 1987 (19.08.87), figs. 1-4; abstract; claim 1. --	1,10, 18
A	EP, A1, 0 140 777 (TEXAS INSTRUMENTS FRANCE) 08 May 1985 (08.05.85), figs. 1,3; abstract; claims 1-9. -----	1,10, 18

 Further documents are listed in the continuation of box C. Patent family members are listed in annex.

* Special categories of cited documents :

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- *E* earlier document but published on or after the international filing date
- *L* document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
- *O* document referring to an oral disclosure, use, exhibition or other means
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Date of the actual completion of the international search

18 May 1994

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ANHANG

zum internationalen Recherchenbericht über die internationale Patentanmeldung Nr.

ANNEX

to the International Search Report to the International Patent Application No.

ANNEXE

au rapport de recherche international relatif à la demande de brevet international n°

PCT/US 94/00770 SAE 85896

In diesem Anhang sind die Mitglieder der Patentfamilien der im obengenannten internationalen Recherchenbericht angeführten Patentdokumente angegeben. Diese Angaben dienen nur zur Orientierung und erfolgen ohne Gewähr.

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La présente annexe indique les membres de la famille de brevets relatifs aux documents de brevets cités dans le rapport de recherche international visé ci-dessus. Les renseignements fournis sont donnés à titre indicatif et n'engagent pas la responsabilité de l'Office.

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